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CAA PAPER 96005

HELICOPTER CRASHWORTHINESS

Study I **A Review of UK Military and World Civil Helicopter Water Impacts over the period 1971–1992**

Study II **An Analysis of the Response of Helicopter Structures to Water Impact**

CIVIL AVIATION AUTHORITY, LONDON

Price: £12.00

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Study II An Analysis of the Response of Helicopter Structures to Water Impact

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REPORT PREPARED BY WESTLAND HELICOPTERS LTD, YEOVIL, SOMERSET AND PUBLISHED BY CIVIL AVIATION AUTHORITY, LONDON, JULY 1996

ISBN 0 86039 667 3

First published July 1996
Reprinted December 1999

Printed and distributed by
Westward Digital Limited, 37 Windsor Street, Cheltenham, England

General Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority, the UK Department of Transport, and the UK Off-Shore Operators Association. The work was instigated at Westland Helicopters Ltd (WHL) Stress Department in response to Recommendations 7 and 8 of the Report of the Helicopter Airworthiness Review Panel (HARP Report – CAP 491), and comprised the following two studies:

I A Review of UK Military and World Civil Helicopter Water Impacts Over the Period 1971 – 1992.

II An Analysis of the Response of Helicopter Structures to Water Impact.

This paper contains unabridged versions of the corresponding Westland Helicopters Ltd Stress Department Reports, SDR 146 and SDR 156 respectively.

The principal conclusions of these studies included:–

- The primary cause of loss of life from helicopter water impacts was drowning (occupant fatalities resulting from excessive crash forces or as a result of structural collapse during an impact were a secondary issue).

- Designing the airframe to remain afloat for sufficient time to enable evacuation following a water impact should be a major objective if occupant survival is to be improved.

In response to the findings of the research reported in this paper, and in response to Recommendation 14.2(g) of the Review of Helicopter Off-Shore Safety and Survival (RHOSS Report – CAP 641), further research to establish the feasibility, techniques and costs of improving the crashworthiness of helicopter emergency flotation systems is currently planned.

Safety Regulation Group

23 May 1996

Study I

A Review of UK Military and World Civil Helicopter Water Impacts over the period 1971–1992

Summary

This paper reviews accidents to UK Military and World Civil Helicopters over the period 1971 – 1992 that have involved impact with water. All occurrences of helicopter water impacts that have resulted in occupants receiving serious or fatal injuries and/or the aircraft sustaining substantial damage have been considered. These criteria meet the minimum requirement for a notifiable accident as defined by Civil and Military airworthiness authorities. Accidents not considered relevant to this study, for example, ground accidents and catastrophic non-survivable accidents, were excluded.

Analyses of accident data were carried out to determine the distribution of impact conditions, accident causes and primary occupant injury mechanisms. The effectiveness of helicopter flotation systems was also reviewed. Mechanical failures were found to be the primary cause of accidents for both military and civil helicopters. These accidents accounted for only a small percentage of occupant fatalities in military helicopter accidents but were the primary cause of fatalities in civil helicopter accidents. Human factor issues (pilot error and disorientation) were found to be the primary cause of occupant fatalities in military helicopter water impacts. In fatal accidents where the cause of death had been established, drowning was found to be the major cause of loss of life.

Helicopter water impacts were categorised into three impact types that accounted for over 70% of all occurrences for which impact conditions were known. Analysis of these impact types is to be undertaken at a later stage in this programme to assess the response of helicopter structures to water impact and to evaluate the level of crashworthiness in current designs. From this work, areas where potential design improvements could be made to increase occupant safety will be identified.

Contents

1 INTRODUCTION

Numerous studies have been carried out over the last 30 years into helicopter crashworthiness and occupant crash survival. This effort has resulted in the development of improved crash survival design criteria and has led to a significant increase in the probability of occupants surviving aircraft crash impacts. The bulk of this effort has to date been directed at the study of helicopter impacts onto solid ground with little emphasis on impacts involving water or non rigid surfaces. However, although ground impacts account for the majority of helicopter accidents, collision with water has been identified as a significant accident category for both military and civil helicopters. From the CAA's World Helicopter Accident Summary (1), for example, 494 civil helicopter accidents are listed for the period 1959 – 1990 with over 24% involving water impact. Similarly, UK military helicopter accident data indicates that for the years 1971 – 1983 over 27% of the 254 accidents involved collision with water (2, 3, 4).

Previous studies have been carried out in the UK into helicopter ditchings and water impact, although with post crash survival as the primary emphasis, techniques for assisting underwater escape, survival equipment and flotation systems for example, have been the focus of attention. Little consideration has been given to improving the probability of occupants surviving the initial aircraft impact with the water surface. The aim of this present study is to review helicopter accidents involving impact with water and to determine impact parameters and primary injury causing mechanisms as an initial step in developing improved crash survival design criteria.

Early investigations of helicopter water impacts suggest that structural damage and occupant injury mechanisms are significantly different from and frequently more severe than helicopter ground impacts of an equivalent velocity. The absence of an effective undercarriage to absorb crash energies in a vertical impact is a major factor in increasing the severity of water impacts. Furthermore, the generally poor hydrodynamic performance of current helicopter designs precludes extensive high speed forward motion in the water that, for a ground impact, may reduce the aircraft kinetic energy through sliding friction. From the data compiled during the preparation of this paper, a study of the response of helicopter structures to water impact is being undertaken. The aim of this work is to identify structural weaknesses and to evaluate levels of crashworthiness in current designs. In addition, areas will be identified where potential design improvements can be made.

2 SOURCES OF DATA

The primary sources of military accident data for this study have been the detailed accident reports prepared by the Royal Navy Aircraft Accident Investigation Unit at HMS Daedalus and a previous review of helicopter ditchings by Reader (5). Other reviews of military helicopter ditchings, namely those of Vyrnwy – Jones in 1989 (2) and Baker and Harrington in 1988 (6) were also consulted during preparation of this paper. Information on helicopter ground impacts was obtained from three reports by Vyrnwy – Jones for Naval, RAF and Army helicopters (2, 3, 4).

For civil helicopter accident data, the CAA's World Helicopter Accident Summary (1) was the primary source. Additional data was provided by the Department of Transport Air Accidents Investigation Branch accident reports, ICAO (International Civil Aviation Organisation) accident reports and US National Transportation Safety Board (NTSB) aviation accident reports.

The accident reports and reviews referenced above contain significantly more information than has been possible to include in this present study. Considerable information is available, for example, on escape problems from ditched helicopters and other post crash survival issues. These references remain a valuable source of data for researchers requiring additional information. The aircraft accident data presented in this paper has been compiled from the best available information and while every effort has been made to ensure the reliability of this data, total accuracy cannot be guaranteed.

Lack of detailed information in accident reports on occupant injuries and structural crashworthiness issues was found to be a significant problem in the preparation of this report. The lack of estimates or calculations of aircraft impact velocities and attitudes, for example, prevented a statistical analysis of impact conditions from being undertaken. In civil helicopter water impacts, the cause of death was established in less than half of the total number of fatal accidents. Similar problems have been reported by Baker and Harrington (6), Hodges (7) and Reader (5) in their reviews of helicopter ditchings. Although it is recognised that for some accidents where the aircraft wreckage has not been recovered, certain information is not available, it is felt that in many cases a detailed description of structural damage to the aircraft and estimates of impact conditions would greatly benefit future studies into helicopter crashworthiness. A detailed account of occupant injuries and their probable cause, would also be a valuable addition to future accident reports.

In addition to the published reports listed above, valuable information was also provided by Lt Cdr Paul Barton from HMS Daedalus, Robert Carter of the Air Accidents Investigation Branch and James Ferguson. Their contributions are gratefully acknowledged.

3 DEFINITIONS AND TERMINOLOGY

Ditching – A forced landing onto water following a loss of power or control. This definition is in agreement with UK military terminology. It should be noted, however, that in civil aviation requirements, a ditching is defined as a controlled alighting on water. This definition is equivalent to the military precautionary alighting on water which considers the controlled alighting to be pre-meditated.

Crash Landing – A landing involving high impact velocities and a significant or total loss of control.

Water Impact – A landing on water that meets one of the above definitions. The term water impact, therefore, includes both ditchings and crash landings onto a water surface.

Survivable Crash – A crash in which the forces transmitted to the occupants do not exceed the limits of human tolerance and in which the structure surrounding the occupants remains sufficiently intact to permit survival.

Significant Survivable Crash – A crash determined to be survivable and in addition, meets one or more of the following minimum injury or damage criteria:

(a) At least one occupant receiving serious injury.

(b) The generation of impact forces likely to cause injury to occupants.

(c) The aircraft structure sustaining substantial damage.

It should be noted that the term survivable means impact survivable. The presence of a post crash fire or loss of life as a result of drowning are not considered factors in determining whether or not an impact is survivable.

4 ACCIDENT CLASSIFICATION

All reported water impact occurrences over the period 1971–1992 involving UK military and world civil helicopters of an AUW greater than 3500 kg were considered in the initial review of accident data.

Whilst every effort was made to include as many accidents as possible, this review is not claimed to be exhaustive due to the heavy reliance on previously published data. The minimum weight classification of 3500 kg ensures a minimum carrying capacity of 11 occupants, i.e. typically 2 crew and 9 passengers.

From an initial population sample of 130 civil and 74 military helicopter water impact occurrences, impacts of a minor nature, i.e. those not meeting the minimum requirements to be classed as an accident, ground accidents and those considered to be non-survivable were excluded. Accidents for which limited or no information was available, were also excluded. These exclusions resulted in a final population sample of 98 civil and 61 military accidents. Of the 32 excluded civil accidents, 16 were fatal (146 fatalities). Of the 13 military accidents excluded, 1 was fatal (4 fatalities).

In line with the accident data analysis procedures adopted in the Aircraft Crash Survival Design Guide (8) and other accident reviews (e.g. 9, 10), non-survivable accidents and those of a minor nature have been eliminated from the analyses carried out in this study. It has been argued that only significant survivable accidents are of interest because it is the many fatalities and serious injuries occurring in these accidents that could be avoided by improved design. Hence,it is in this category of accident that the greatest benefits and improvements could be made.

Mens (11), however, argues that setting an initial bias on the analysis by eliminating certain occurrences, distorts the limits established for a given percentile accident. By excluding low severity accidents, for example, the 50th and 95th percentile potentially survivable crash velocities are artificially raised. A fundamental rule of any statistical analysis, Mens argues, is to examine a sample representative of the entire population.

Without knowing the details of an accident, it is frequently difficult to determine whether an impact is significant, survivable or minor. Certainly impact velocity is not a factor in determining how an accident should be categorised. A study carried out by Coltman et al (9), for example, has shown that 35% of significant survivable civil helicopter accidents in the US involved a vertical velocity below 5ft/sec. Normally this velocity would be well within the capability of most helicopters landing gears.

It is also difficult to set limits on what accident should or should not be included when a decision has to be based solely on the extent of structural damage or occupant injury. Structural damage and injuries may, for example be due to factors other than impact forces. It has been observed in this present study that well controlled low velocity ditchings may still result in substantial structural damage and serious injury under adverse sea states. This difficulty in accurately determining what accidents should be included in an analysis may possibly account for the wide variations in the estimated values of the 95th percentile potentially survivable water impact for US Naval helicopters as defined in references 10 and 12. Vertical impact velocities for this crash severity vary from 28ft/s (10) to 50ft/s (12) with an even greater difference in the longitudinal impact velocities, i.e. 72 ft/s (10), 124 ft/s (12).

Lack of uniformity in the criteria by which accident severity is judged may also account for observed variances in accident data. Reference 9, for example specifies at least 1 injury of a minor or serious nature as one criteria for a significant survivable accident. Reference 12, however, specifies that at least 1 occupant receives major injury as the lower limit of a significant survivable accident.

Because the criteria for a survivable accident are difficult to apply, accidents are frequently assigned to this category if there is at least 1 survivor and at least 1 serious injury. However, occurrences have been reported of occupants miraculously surviving accidents that, because of their severity, (mid air collisions, for example) would normally be classed as non survivable. Considerable differences in how accidents are classified therefore exist. Because accident data for this study has been compiled from more than one source, consistent accident data classification cannot be guaranteed. Differences in accident data classification can also make comparisons between individual accident reviews unreliable and hence such work should only be undertaken with caution.

A factor that is likely to distort any comparison between water impacts and ground impacts is the often trivial nature of the emergency that leads to an accident. A controlled ditching as a result of a minor electrical problem for example, may result in severe damage or the total loss of the helicopter. A similar problem affecting a helicopter operating over land would usually only result in a precautionary landing and would probably not feature as an accident statistic.

5 DATA ANALYSIS

5.1 Military Accident Data

Sixty one occurrences of UK military helicopter water impacts over the period 1971–1992 have been included in this analysis and are listed in Table 1. This table includes a description of the cause of the accident, the number and severity of injuries and brief notes on the type and severity of impact. These notes are intended to give an indication of the conditions prior to impact, for example, the degree of control. Information on impact severity has been taken primarily from Reference 5. A light impact is defined here as one in which the helicopter is under a controlled descent even though directional control may be lost. For a heavy impact, the helicopter is assumed to have lost a substantial degree of control or has impacted the water in an adverse attitude. An out of control classification signifies a total loss of control and includes mid air collisions and free falls from altitude. The fourth category of impact, fly-ins, are primarily high forward speed, gradual rate of descent impacts with the aircraft approaching the water surface at a shallow angle. These accidents are invariably the result of pilot error or disorientation.

The flotation and helicopter inversion data shown in Table 1 has again been taken from Reference 5. Immediate inversion indicates that the helicopter inverts before the occupants could escape and typically in less than 15 seconds. Delayed inversion indicates that evacuation was complete before inversion occurred; inversion times here are generally greater than 15 seconds. The term serviceable flotation refers to a successful deployment and prolonged inflation of the flotation gear. A partial inflation indicates that at least one of the flotation bags either failed to inflate or deflated shortly after deployment. The accidents listed in Table 1 have been categorised with respect to accident cause, impact type and severity.

5.1.1 *Classification of Accidents with Respect to Accident Cause*

An analysis of the cause of military helicopter water impacts is shown in Table 2. The most significant cause of accidents was determined to be mechanical failure with engines (31·1%), main rotor transmission (11·4%) and tail rotor (11·4%) being the most vulnerable components. Included under main rotor transmission failures are both mechanical and lubrication failures.

As shown in Table 3 the majority of accidents caused by mechanical failure resulted in low severity impacts and accounted for only 3 (6·5%) fatalities. In the majority of cases adequate warning of an impending impact would be given such that the aircraft could be prepared and ditched under control. Table 4 shows that 23 of the 61 impacts were controlled ditchings. For example, of the 7 main rotor transmission failures, 6 resulted in successful controlled ditchings with no injuries. Of the 19 engine failures, 7 resulted in successful controlled ditchings with a further 9 resulting in a vertical descent onto water with a limited degree of control. Three engine failure accidents resulted in 4 serious injuries. A fourth accident, categorised as out of control, resulted in 3 fatalities. For naval helicopters, particularly those in an ASW role, a significant proportion of airborne time is spent in the hover. In this phase of flight, engines and main rotor transmissions are highly loaded and hence the hover is associated with a high incidence of failure of these components. The 7 tail rotor failures resulted in 7 serious injuries but no fatalities.

Failure and malfunctions in other aircraft systems accounted for 11 of the 61 accidents as shown in Table 2. Because these inflight emergencies did not generally affect control of the aircraft, controlled ditchings were executed in the majority of cases. One accident, however, caused by a computer failure, resulted in 2 fatalities in a high speed fly-in accident.

The 3rd major category, pilot error and disorientation, accounted for 14 of the 61 accidents and resulted in 87% of the fatalities and nearly 50% of the serious injuries. Five of the 14 accidents in the category of pilot error and disorientation were high forward speed fly-in accidents with the aircraft making a gradual descent into the water surface. Impacts were at a shallow angle with the water surface and extremely severe. All 5 accidents were fatal resulting in 11 fatalities. A further 3 accidents involved both vertical and forward velocity. The remaining 6 accidents were either controlled ditchings or out of control accidents.

In addition to the 14 accidents where pilot error or disorientation was clearly identified as a casual factor in the accident, 5 further accidents were considered to have had contributory causes from pilot error. Two of these accidents were fatal resulting in the loss of 5 lives. In 3 accidents, although mechanical failure was present, the pilot failed to follow the required procedures to correct the situation.

Failure to maintain rotor RPM in an attempted autorotative descent and shutting down the wrong engine following a single engine failure are two examples.

Comparing the distribution of accident causes established in this study with other accident reviews, shows a similar percentage of accidents resulting from mechanical failure. Brooks (13), for example has shown that 52% of Canadian Navy helicopter ditchings were the result of mechanical failure in the period 1952 – 1990. Reader (5) has reported that 50% of Royal Navy helicopter ditchings over the period 1972–1988 were the result of failures to the power plant or transmission. Pilot error has been shown to be a major cause of military helicopter accidents in studies by Steele-Perkins (15), Day (14) and Brooks (13) where between 23% and 46% of water impacts have been shown to be the result of pilot error. The maritime environment has been shown to be a significant factor in inducing disorientation among aircrew (16).

5.1.2 *Classification of Accidents with Respect to Impact Type*

An analysis of military helicopter accident data with respect to impact type is shown in Table 4. Three impact categories were identified that accounted for over 70% of water impacts. Controlled ditchings can be seen to account for 37·7% of water impacts. In a controlled ditching the aircraft is considered to be under full control such that the pilot is able to limit the rate of vertical descent to an acceptable figure (e.g. 5 ft/s). Forward velocities are dependent on whether the helicopter is under power or autorotating but are generally below 30kts. Aircraft attitudes are invariably level in roll and pitch except for autorotative descents where flare out prior to touchdown may result in a slight nose up pitch attitude. All controlled ditchings are classed as light with no serious injuries and are well within the structural capability of the airframe.

The vertical descent under limited control category accounted for 27·8% of water impacts. There were no fatalities in accidents in this category although 11 serious injuries were reported. As the aircraft is considered to be under partial control, impact velocities were higher than for controlled ditching but generally still within the capability of the airframe structure. Aircraft forward velocity is again generally low but impact attitudes may involve pitch and roll angles dependent on the degree of control. In addition, the aircraft may be yawing on contact with the water surface if yaw control has been lost. Of the 17 accidents in this category, 4 were classed as heavy. Three of these impacts were the result of tail rotor failures and accounted for 7 of the serious injuries.

Fly-in accidents accounted for 8 of the 61 accidents producing 34 fatalities and 9 serious injuries. Twenty one fatalities and 8 serious injuries occurred in one accident. Five of these accidents were high forward speed, shallow angle impacts with the water surface and extremely severe. The remaining 3 accidents involved significantly lower forward impact velocities and occurred while the aircraft was either in the hover or shortly after take-off.

Of the remaining 13 accidents, 7 were uncontrolled impacts and 4 were insufficiently documented to allow classification.

5.1.3 *Analysis of Occupant Injuries*

Of the 61 military helicopter accidents recorded in the period 1971–1992, 13 (21·3%) were fatal resulting in 46 fatalities.

Thirty eight deaths (82·6% of the total) were the result of drowning. The remaining 8 fatalities resulted from impact injuries in which 2 were attributable to seat failure, 2 from blade strike and 3 from multiple injuries sustained in catastrophic out of control accidents.

Thirty four (73·9%) fatalities occurred in accidents that were categorised as either controlled ditching, vertical descent with limited control or fly-in accidents. The remaining 12 fatalities occurred in accidents where the aircraft was essentially out of control.

There was a total of 18 accidents that involved fatal or serious injuries. Seven of these accidents resulted in 20 serious injuries; 12 injuries were spinal compression fractures, 2 involved other bone fractures and 6 were unknown. The high incidence of spinal compression fractures reflects the high vertical impact forces associated with helicopter water impacts. This finding is broadly in agreement with the findings of Vyrnwy-Jones (2) where spinal injuries were found to account for 73·3% of all major injuries in UK Navy helicopter water impacts. These figures, however, are significantly higher than the spinal injury rate observed for army helicopter accidents. A summary of occupant injury data is shown in Table 5.

Drowning was shown to be the major cause of death in survivable US Navy helicopter water impacts in a study by Glancy (12) where 54·7% of fatalities were due to drowning and a further 38·0% were lost at sea presumed drowned. Rice and Greear (17) reported that 84·1% of fatalities in ditched US Navy helicopters over the period 1969–1972 were identified as either drowned (39·6%) or lost at sea (44·4%). Forty percent of those recovered drowned or lost at sea were last seen still in the aircraft indicating that the inability to escape, either because of incapacitation or disorientation, is a major issue.

5.1.4 *Analysis of Helicopter Flotation Systems*

Of the 61 ditchings, 35 (57·3%) resulted in immediate inversion, 15 (24·5%) were delayed inversions and in a further 9 cases the aircraft did not invert. Seven ditchings involved helicopters without flotation systems fitted and all resulted in immediate inversion. The 16 occurrences where a flotation system was fitted but not used also resulted in immediate inversion. In the 28 cases where the flotation system was successfully deployed, there were 5 cases where the helicopter inverted immediately. Fourteen of the above 28 cases involved controlled ditching and it was from this population that the 5 cases of immediate inversion occurred.

The number of ditchings resulting in immediate inversion calculated above, is broadly in agreement with a Boeing Vertol study (see Reference 24) into 200 US Navy Marine helicopter ditchings where it was revealed that more than 50% of aircraft inverted and/or sank in less than one minute. Vyrnwy-Jones (2), in a study of 53 Royal Navy helicopter ditchings between 1972 and 1984 calculated that 47% of helicopters either sank or inverted immediately after water impact.

The reason for 16 occurrences of the flotation system not being used is unclear. It is possible that in a number of cases the pilot had considered that a water take-off was feasible and hence was reluctant to deploy flotation equipment. Evidence indicates that in at least one case the pilot had attempted to deploy flotation gear but without success. In the remaining cases, pilot disorientation or incapacitation was a likely explanation for the failure to deploy flotation gear. These examples provide strong evidence for the automatic deployment of flotation aids when a helicopter contacts a water surface. At least 2 methods of automatically deploying flotation systems, in addition to a manual activation capability have been recommended by Reader (5).

To be effective, the flotation system must withstand the initial impact with the water surface and keep the helicopter upright and afloat for long enough to enable occupants to evacuate. The high incidence of immediate inversions (over 57%) reflects the poor performance of flotation systems fitted to helicopters over the period 1971–1992. Evidence shows that in some instances flotation bags were damaged by the initial water impact and in other cases were made ineffective because of the failure of the structure to which they were attached. Failures of flotation systems as a result of wave action in the post impact phase have also been recorded.

Because of inherent instability of current helicopter designs, e.g. high centre of gravity and narrow fuselage, there is a strong likelihood that the helicopter will invert even when successfully ditched in calm conditions. Main rotor blade strike with the water surface due to wave motion or excessive roll of the aircraft in the water and even application of the rotor brake can generate an overturning moment of sufficient magnitude to invert the helicopter. In sea states of 3 or greater, it has been reported that the majority of helicopters invert and/or sink regardless of how well controlled the ditching may have been (2).

5.1.5 *Comparison Between Military Helicopter Water Impacts and Land Based Impacts*

From three reviews of helicopter accidents (2, 3, 4) for the 3 UK armed forces (RAF, RN, Army Air Corp), a study was made of the relative proportion of water impacts and accidents involving impact with the ground. Unfortunately no published reviews were available for UK military ground impacts in recent years, and as a result, the comparison was limited to data for the period 1971–1982. It should be noted that the accident reviews contained in reference 2, 3, and 4 have employed different classification criteria in their data analyses to those adopted in this present study. Hence, comparison between these different reviews, even if they involve apparently similar populations, should be carried out with caution.

From the three accident reviews referenced above, a total of 231 accidents involving UK military helicopters were reported in the period 1971–1982. These accidents accounted for 95 fatalities. Of these 231 accidents, 169 were land impacts and 62 were water impacts. 15·4% of land impacts were determined to be fatal compared to 16·1% of water impacts.

The 169 land impacts involved 434 occupants; fifty eight occupants were fatally injured resulting in a survival rate of 86·6%. For water impacts there were 37 fatalities from a total of 253 occupants, producing a marginally lower survival rate of 85·3%. This difference in survival rates is not considered to be significant. The survival rates in Royal Navy helicopter accidents were calculated to be 85·2% for water impacts and 86·3% for land impacts (5); again the difference is not considered significant.

Brooks (13) has calculated a survival rate of 76% for Canadian Military helicopter ditchings over the period 1952–1990. For US Navy/Marine Corps helicopter ditchings in the years 1977–1990, Barker (19) has shown a survival rate of 83% in 115 survivable accidents. A study of US Army helicopter accidents over the period 1979 – 1985 (18) has demonstrated an occupant survival rate of 87·1% in 298 significant survivable accidents. In comparison, the 61 helicopter water impacts reviewed in this present study produced an occupant survival rate of 83·1%.

A comparison of land and water impacts has shown a significant difference in the distribution of major injuries. Whereas spinal compression fractures have been shown to be the most frequently identified serious injury to occupants in water impacts (see 5.1.3), for land impacts, spinal injury accounted for only 16·5% of serious and fatal injuries in a study of US Army helicopter accidents (8). A study of UK Army Air Corps land impacts has revealed that 18·0% of serious injuries are spinal in nature (4). Both these references have shown that head impacts are the most significant cause of serious injuries in army helicopter land impacts.

As discussed in 5.1.3, 73·3% of major injuries in RN helicopter ditchings were spinal injuries (2). It was also shown in the same study that if all RN accidents are considered (water, land and deck), then the percentage of spinal injuries falls to 50%. Day (14) also identified a reduced figure for spinal injuries of 34% for all RN helicopter accidents over the period 1960 – 1969.

A study of US Navy helicopter ditchings by Coltman (10) concluded that the most serious crash hazard resulted from structural failure of crew and troop seats that allowed the body to strike adjacent structure. Of the total number of major and fatal injuries, 27·4% were considered to be the result of seat or restraint failure. Interestingly, only 10·5% of major/fatal injuries were found to be the result of excessive decelerative force.

A study of US army helicopter accidents over the period 1979 – 1985 (18) has also revealed the most common cause of injuries to be secondary impacts caused by inadequate restraint or structural collapse. In survivable accidents, 60·1% of injuries were considered to be the result of the occupant striking, or being struck by aircraft structure. As for water impacts, occupants receiving excessive decelerative forces accounted for only a small percentage of injuries (12·3%). The most frequently identified deficiencies contributing to occupant injury were restraint systems (39·7%) and seats (23·4%).

Several studies have shown a high incidence of injuries to lower and upper body extremities in army helicopter impacts. For example Shanahan (18) has shown that leg injuries account for 27·4% of the total number of injuries. Vyrnwy-Jones (4) has calculated a figure of 16·0% for similar injuries. Although these injuries are classified as severe for land impacts they are unlikely to be hazardous to life, unless a post crash fire is also present. In water impacts, however, such injuries may incapacitate an occupant to the extent that he is unable to evacuate the aircraft. If the aircraft subsequently inverts or sinks, then the outcome is invariably fatal; the cause of death will be drowning with the original injury going unrecorded.

As discussed in 5.1.1, pilot error has been shown to be a major cause of aircraft water impacts (23–46%). Studies of UK and US army helicopter ground impacts, however, have shown that a considerably higher percentage of accidents are the result of pilot error. Singley and Sand (20) have shown that over the period 1968–1975, 71% of US army helicopter accidents were the result of flight crew errors. For UK Army Air Corps helicopter accidents, 75% were attributable to pilot error (4).

5.2 Civil Accident Data

Ninety eight notifiable water impacts to world civil helicopters over the period 1971 – 1992 have been included in this analysis and are listed in Table 6. This table includes a description of the cause of the accident, the number and severity of injuries and a description of the type of impact. The same categories of impact type as that used for the military data has been adopted here, these being controlled ditching, descent with limited control, fly-in and out of control. Where available, information on helicopter flotation system effectiveness is also presented. However, of the 98 accidents, information on post impact flotation was only available in 56 cases. The terms used to describe helicopter flotation performance are as those defined for military helicopters in 5.1. The accidents listed in Table 6 have been categorised with respect to accident cause and impact type.

5.2.1 *Classification of Accidents with Respect to Accident Cause*

An analysis of the cause of civil helicopter water impacts is shown in Table 7. The most significant cause of accidents was found to be mechanical failure with engines (19·3%) and main rotor transmission (17·3%) showing the highest incidence of failure. Failure or malfunction in aircraft systems other than power plant and transmission accounted for 14·2% of accidents. Accidents attributable to pilot error or disorientation accounted for 24·4% of the total number of accidents. An NTSB study (21) has shown that for US civil helicopters over the period 1977 – 1979, 39·5% of accidents were attributable to mechanical failure in the power plant and transmission. A similar figure of 41% for mechanical failures was calculated by Balfour (22) in a study of 27 UK civil and military helicopters between 1956 and 1975. These figures are in reasonable agreement with those determined in this present study.

From Table 7 it can be seen that the 55 accidents resulting from mechanical failure accounted for 60·3% of the total number of fatalities. Pilot error accounted for 30·1% of fatalities, a significantly smaller percentage than that shown for military accidents. In addition to the 24 accidents where the cause was determined to be pilot error or disorientation, there were a further 6 accidents where the pilot was considered likely to have been a casual factor. Of these 6 accidents, 3 were fatal accounting for 19 fatalities. These accidents, however, even if included in the pilot error category would not have significantly affected the percentages quoted above.

In the review of US civil rotorcraft accidents discussed in Reference 21, the pilot was cited as a cause or related factor in more than 64% of the total number of accidents. This study included both water and land impacts. This figure of 60% is significantly greater than the 30·1% determined for pilot error accidents in this study.

5.2.2 *Classification of Accidents with Respect to Impact Type*

An analysis of civil helicopter water impacts with respect to type of impact is shown in Table 8. Controlled ditchings accounted for 29·5% of water impacts. The second largest impact type category was vertical descent with limited control that accounted for 25·5% of the water impacts analysed. The total number of accidents in these two categories (55%) is broadly similar to that found for military helicopters (64%). However, whereas military helicopter controlled or limited control impacts did not result in any fatal accidents, Table 8 shows that for civil helicopters over 15% of fatalities were accounted for in these two categories.

Fly-ins and uncontrolled impacts accounted for 17·3% and 25·5% respectively of civil helicopter water impacts compared to 13·1% and 11·4% for UK military helicopter water impacts. Twenty three percent of fatalities occurred in fly-in accidents; uncontrolled impacts accounted for 58·5%. These proportions again are significantly different than the 73·9% and 26·0% of fatalities in fly-in and uncontrolled impacts for military helicopter accidents.

5.2.3 *Analysis of Occupant Injuries*

Of the 98 world civil helicopter water impacts over the period 1971 – 1992, 48 (48·9%) were fatal resulting in 338 fatalities. This fatality rate is over twice that for UK military helicopters. In accidents where the cause of death had been established (24 out of 98), 56·7% of fatalities were the result of drowning. Of the 902 occupants involved in the 98 accidents, 338 lost their lives resulting in a survival rate of 62·5%. This figure is significantly lower than the 83·1% survival rate calculated for military helicopters.

Of the 98 water impacts, 52 involved serious or fatal injuries; 22 of these accidents accounted for 46 serious injuries. In 17 of the 48 fatal accidents all occupants were killed. A breakdown of the distribution of occupant injuries showed that of the 338 fatalities, 281 were passengers and 57 were crew.

As shown in Table 8, 276 fatalities (81·6%) occurred in accidents that were categorised as fly-in or uncontrolled. Fifty one fatalities (15·0%), however, occurred in impacts classed as controlled or partially controlled. Insufficient information was available to enable a detailed analysis of injury mechanisms to be carried out. However, in 10 fatal accidents a total of 130 seat failures were recorded. In an accident to an S61 in July 1990 (see accident 11 in Table 6) in which 6 occupants out of 13 died, it was found that all occupied seats showed some form of impact damage. All of the passengers who died were shown to have occupied seats that collapsed on impact. Furthermore, 7 of the 10 fatal/serious injuries were due to flailing of the body that resulted in contact injuries.

5.2.4 *Analysis of Helicopter Flotation Systems*

Insufficient information was available to carry out a detailed analysis of civil helicopter flotation effectiveness. Of the 98 accidents included in this analysis, however, limited information was available in 56 cases. In 37 water impacts the aircraft inverted or sank before evacuation was completed. In the remaining 19 cases, the aircraft remained afloat and upright for long enough to enable occupants to evacuate. In the 37 cases of immediate inversion, 26 were fatal accidents involving 181 fatalities. For the cases where a cause of death had been established (133 out of 181 fatalities), drowning was identified in 83 cases. In a review of North Sea helicopter ditchings by Ferguson and reported in Reference 24, 28 ditchings between 1969 and 1987 resulted in a survival rate of 62%. Eleven (39·2%) of the ditched helicopters were reported to have inverted or sank immediately.

5.2.5 *Comparison Between Civil Helicopter Water Impacts and Land Based Impacts*

A comparison between land and water impacts for UK and world civil helicopters was not possible due to lack of published reviews or summaries on land impacts. Although raw data was available from the CAA's World Helicopter Accident Summary and ICAO sources, analysis of this data was considered to be outside the scope of this present study. Findings from US studies, however, are considered relevant and worthy of inclusion.

In a study of US civil helicopter accidents over the period 1974 – 1989 (9) 9·7% of accidents where the impact scenario was known were determined to be water impacts. Survivable water impacts, however, accounted for 64·7% of fatalities. High vertical velocity land impacts accounted for only 5·8% of fatalities. For serious injuries, the high vertical velocity land impact category was shown to be the most severe with 45·1% of all serious injuries. Excessive vertical forces caused almost half of the injuries in this accident type. In comparison, water impacts accounted for 20·9% of the total number of serious injuries.

As discussed in 5.2.1, Reference 21 established the pilot as a cause or related factor in over 64% of US civil helicopter accidents in the period 1977 – 1979 in which a probable cause was determined. This corresponds reasonably well with the figures for UK and US military land impact data. Reference 11 quotes a figure of 71·2% for US military helicopter pilot error accidents over the period 1968 – 1975; reference 4 quotes a figure of 75% for UK Army Air Corps helicopter pilot error accidents over the period 1971 – 1982.

In this water impact study, however, only 24·4% of civil and 23% of military helicopter accidents were attributable to pilot error. This difference may in part be explained by the high incidence of pilot error accidents in land based impacts where the aircraft hit obstacles such as trees and wires. Reference 21, for example, indicates that 17·8% of land based civil helicopter accidents involve collision with obstacles (wires, trees, poles). Over water flight is generally free from such obstacles. A paper by Bender (23) has shown that 27·2% of accidents involving MBB helicopters that were attributable to pilot error, were the direct result of collision with obstacles.

6 DISCUSSION

This study has reviewed water impacts over the period 1971–1990 involving world civil and UK military helicopters. Analyses were restricted to accidents that resulted in substantial damage to the helicopter and/or the occupants receiving serious or fatal injuries. The 98 world civil accidents analysed resulted in 338 fatalities and a survival rate of 62·5%. An analysis of 61 UK military helicopter water impacts revealed 46 fatalities and a significantly greater survival rate of 83·1%. Similar survival rates for US and Canadian military helicopter water impacts (83% and 76% respectively) have been demonstrated by Barker (19) and Brooks (13). Published data on civil helicopter survival rates was unfortunately only available for fatal accidents involving both water and land impacts. This study of US civil helicopters carried out by the National Transportation Safety Board (21) revealed a survival rate of 27·6%. This compares with a figure of 33·5% for fatal water accidents in this present study.

The primary cause of helicopter water impacts was shown to be mechanical failure in engines, transmission and rotor systems. For world civil accidents, 56·1% were the result of mechanical failure in these components; for UK military helicopters the figure was 55·7%. The second most common cause of accidents was determined to be pilot error for both civil water impacts (24·4%) and military water impacts (22·9%). These figures are significantly lower than the frequency calculated for pilot error accidents on land where figures of the order of 70% have been demonstrated (4, 20). Although the maritime environment is known for its potential to induce disorientation, it is believed that the high number of pilot error land impacts are, at least in part, the result of collision with obstacles and heavy landings.

Although only a small percentage of military accidents were found to be the result of pilot error (22·9%), these accidents accounted for 86·9% of fatalities; mechanical failures that accounted for 55·7% of accidents, resulted in only 6·5% of fatalities. A different distribution of fatality causes was observed in civil helicopter water impacts. Pilot error, that accounted for 24·4% of accidents, resulted in 30·1% of fatalities. Mechanical failure accidents (56·1%) produced 60·3% of the total number of fatalities in civil helicopter water impacts.

A possible explanation for this difference is that in military helicopters, where pilots are trained in simulated engine and tail rotor failures, for example, they are better able to respond to real emergencies. Table 4 and 8, for example, show that of the 61 military helicopter water impacts, 37·7% are controlled ditchings, whereas for civil helicopters, 29·5% of the 98 water impacts were controlled ditchings. Furthermore, 25·5% of civil helicopter water impacts were classed as out of control compared to only 11·4% for military helicopter accidents.

The cause of death in the majority of accidents analysed where a cause had been identified was shown to be drowning. In military helicopter water impacts, 82·6% of fatalities were due to drowning; 56·7% of fatalities in civil helicopter water impacts were the result of drowning. It should be noted for civil helicopter accidents, however, that the cause of death was identified in only 48% of the fatalities analysed. It can be seen from these results that the high fatality rate associated with helicopter water impacts is not an indication of the severity of impact or the magnitude of impact forces but rather reflects the scale of post crash survival problems.

When a helicopter ditches into water it frequently inverts and rapidly sinks. This study has shown that in approximately 60% of military and civil helicopter water impacts, the aircraft inverts or sinks immediately or at least before occupant evacuation was completed. A consequence of this rapid inversion or sinking is that the majority of survivors in water impacts would have had to have made some form of underwater escape. It has been reported that even if the crew and passengers are uninjured, escape is frequently hindered in such cases by loss of vision, disorientation and panic if the occupants have not been trained in underwater escape (2). Occupants whose evacuation is further hindered by debris and difficulty in releasing restraint harnesses, commonly perish (24).

Rice and Greear (17) have reported the inrush of water as the main problem in escaping from a submerged helicopter from interviews with survivors. This, often coupled with disorientation and difficulties in reaching or opening escape hatches, was reported by 50% of survivors of US navy helicopter ditchings. The high incidence of escape difficulties arising from the inrush of water has been noted as a cause for concern in other studies (5, 6).

Injuries to occupants would present a further hindrance to evacuation from a submerged or inverted helicopter. Contact between occupant and adjacent helicopter structure has been shown to be a major cause of injuries in both civil and military land impacts (4, 9, 10, 18). These contact injuries are typically the result of seat failure, structural collapse or inadequate restraint that allows excessive flailing of the body extremities.

The extent to which these injuries at a non-fatal level have contributed to the high incidence of drowning in water impacts is not known. What has been shown, however, is the high incidence of spinal injuries in military helicopter water impacts. This finding is in disagreement with a number of studies into military helicopter land impacts and is only substantiated by other UK water impact studies (5). The reason for the high frequency of spinal injury in water impacts may possibly be that the more incapacitating injuries (i.e. contact injuries) do not appear in the injury statistics if subsequent loss of life is attributable to drowning.

The fact that the majority of fatalities occurring in water impacts are due not to impact forces but are the result of drowning, indicates the need for improved flotation. Not only would improved helicopter flotation provide increased time for occupants to evacuate, it would also offer occupants trapped in the fuselage a greater probability of being rescued. To be effective, flotation equipment must keep the helicopter afloat and upright for long enough to enable occupants to evacuate. It must also be designed to withstand the impact forces generated on contact with a water surface. Failure to deploy the full flotation system, or subsequent deflation following a successful deployment as a result of impact damage, are major causes of helicopter inversion. From the observation that over 50% of helicopter water impacts resulted in rapid inversion or sinking (see also References 5, 24), the current standards of flotation system in both civil and military helicopters are considered inadequate. The practice of designing flotation systems for precautionary alightings onto water or well executed controlled ditchings in relatively calm sea states, does not reflect the severity of the large number of water impacts in which the lives of the occupants are at risk.

Improved flotation can only be an effective survival measure if the aircraft fuselage withstands the initial impact with water and occupants remain within the aircraft. Fuselage break up on impact with a water surface and occupants ejected from the aircraft (often still strapped in their seats) has been shown to result in a significant number of fatalities due to drowning in survivable accidents in both this and other studies (2, 24, 25). The nature of impact forces resulting from impact with a water surface is significantly different from and frequently more severe than land impacts of an equivalent velocity. Water impact forces are generated, for example, from pressure loads rather than mass inertia as in land impacts. Detachment or displacement of large mass items such as engines and main rotor transmission which occur under excessive inertia forces are seldom recorded in helicopter water impacts. If the structural failures observed in water impacts are to be prevented, or at least made less hazardous, a better understanding of the response of structures to water impact is required. A requirement for designers to consider water impact as a crash case is also needed if changes to current design practices are to be realized.

From the results of this study improved flotation is considered to be the primary factor in increasing occupant survival in helicopter water impacts (see also references 5, 12). The second area where improvements could benefit occupant survival is in the design of seats and restraints. Improved occupant restraint (e.g. the provision of upper torso restraints for passengers) could reduce contact injuries by reducing the flail envelope for arms, legs and head (10, 18). Improved restraint would also, it has been argued, stabilise the occupant in his seat and minimise buffeting and disorientation against an inrush of water and during aircraft inversion (24). Restraining an occupant in an upright position in his seat during impacts involving significant vertical forces, would also reduce the probability of spinal injuries.

Improved occupant restraint can only be of benefit in survival terms if the seat structure itself does not allow the hazardous displacement of an occupant. Failure of the seat structure or seat to floor attachments have been shown to be a major contributory factor to occupant injuries in survivable US civil and navy helicopter accidents (9, 10). Following a civil S61 accident in 1983 in which 20 occupants lost their lives (see accident number 51 in Table 6), seat failures were identified as a significant hazard to occupant survival. The Air Accidents Investigation Branch Accident Report (26) recommended that requirements concerning the strength of helicopter passenger seats be reviewed.

As noted earlier, the lack of detailed accounts in accident reports of structural crashworthiness issues, occupant injuries and their probable causes, has imposed significant limitations on the scope of this paper. The almost total lack of calculated or estimated impact parameters such as velocity and attitude, has, for example, prevented a statistical analysis of impact conditions from being carried out. One objective of this analysis was to have been the definition of the level of crashworthiness in current helicopter designs in terms of potentially survivable impact velocities. This has not been possible for the above reasons. It is considered that more detailed accident reporting for both civil and military helicopter accidents would greatly benefit future studies in the area of helicopter crashworthiness and occupant crash survival.

7 CONCLUSIONS

(i) Over 50% of UK military and 56% of world civil helicopter water impacts resulted from mechanical failure to engines, rotor system and transmissions. For world civil helicopter water impacts, 60.3% of fatalities resulted from these accidents.

(ii) Pilot error and spatial disorientation was found to be the second most significant cause of water impacts for both UK military (22.9%) and world civil helicopters (24.4%). This class of accident accounted for 86.9% of fatalities in UK military helicopter water impacts.

(iii) The majority of fatalities in both world civil (56.7%) and UK military helicopter water impacts (82.6%) were attributable to drowning where a cause of death had been identified. Although drowning was recorded as a cause of death in these instances, factors behind why these occupants drowned were invariably not investigated. Incapacitation due to injury and inability to escape through disorientation, entrapment and jammed/obstructed exits have been cited in some cases as probable causes of drowning in helicopter water impacts.

(iv) Compression fractures of the spine were found to be the most frequent non-fatal serious injury to occupants in UK military helicopter water impacts. Seat failures were identified as a significant hazard to occupant survival in both civil and military helicopter accidents. Improved occupant restraint and seat design to prevent occupants from experiencing injurious deceleration levels and also to prevent incapacitating contact injuries is considered to be a significant factor in increasing occupant survival.

(v) In helicopter water impacts, where information on flotation system effectiveness was available, over 50% of occurrences resulted in the helicopter inverting or sinking before evacuation of occupants was completed. A significant number of accidents, therefore, involved underwater escape. Previous studies have shown that an inrush of water, contributing to disorientation and difficulties in reaching and opening escape hatches, is the major hazard facing survivors in inverted or submerged helicopters.

(vi) Improved flotation is considered to be the most significant factor in increasing occupant survival in helicopter water impacts. This could be achieved by improving the robustness and reliability of current systems (flotation bags and inflation mechanisms) and ensuring that such systems are better able to withstand representative water impact conditions.

(vii) It is recommended that UK civil and military helicopter accident reporting procedures be revised to include an analysis of impact parameters and a more detailed account of structural crashworthiness issues. Further useful data could be gained from the inclusion of a detailed description of occupant injuries and their probable cause. This information would greatly assist future studies into helicopter crashworthiness and occupant crash survival.

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List of Tables

Table 1: UK Military Helicopter Water Impacts 1971–1992

	DATE	AIRCRAFT	TOTAL ABOARD	INJURIES F	S	MIN	CAUSE	NOTES	IMPACT	FLOTATION	INVERSION
1	10-9-91	SEA KING	4	–	–	4N	MRGB OIL FAILURE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	DELAYED
2	1-6-91	SEA KING	7	–	–	7N	PILOT ERROR	CONTROLLED DITCHING	LIGHT	SERVICEABLE	DELAYED
3	1-6-90	LYNX	3	–	(2M, 1N)		HARPOON FAILURE	ROLLED OFF DECK, HIT SEA INVERTED	LIGHT	– – – – – – – – – –	– – – – –
4	13-10-88	SEA KING	4	2D	1	1M	CREW DISTRACTION	FLOWN INTO SEA, HIGH FORWARD SPEED	FLEW IN	NOT USED	IMMEDIATE
5	10-3-88	LYNX	2	2D	–	–	DISORIENTATION	FLOWN INTO SEA, HIGH FORWARD SPEED	FLEW IN	SERVICEABLE	IMMEDIATE
6	3-2-88	SEA KING	4	–	–	4N	TAIL ROTOR FAILURE	DESCENT FROM HOVER WITH A/C YAWING	LIGHT	SERVICEABLE	IMMEDIATE
7	16-10-87	WESSEX	3	–	1	2N	WATER INGESTION	DESCENT FROM HOVER WITH LTD. CONTROL	LIGHT	SERVICEABLE	DELAYED
8	23-7-87	SEA KING	6	–	–	6N	ENGINE FAILURE	DESCENT FROM HOVER WITH LTD. CONTROL	– – – – –	– – – – – – – – – –	– – – – –
9	24-2-87	SEA KING	3	(1D, 2I)		–	DISORIENTATION	NOSE DOWN IMPACT FROM HOVER	HEAVY	NOT USED	IMMEDIATE
10	5-11-86	WESSEX	4	(2D, 1I)		1N	DISTRACTION	FLOWN INTO SEA, HIGH FWD SPEED	FLEW IN	NOT FITTED	IMMEDIATE
11	26-10-86	SEA KING	3	–	(1M, 2N)		FUEL STARVATION	VERTICAL DESCENT UNDER LTD CONTROL	LIGHT	NOT USED	IMMEDIATE
12	26-9-84	SEA KING	4	–	–	4N	ENGINE FAILURE	CONTROLLED DITCHING FROM HOVER	LIGHT	PARTIAL INFLATION	NO
13	4-1-84	LYNX	2	2i	–	–	DISORIENTATION	FLOWN INTO SEA, HIGH FORWARD SPEED	FLEW IN	NOT FITTED	IMMEDIATE
14	4-5-83	LYNX	4	–	4	–	TAIL ROTOR FAILURE	VERTICAL DESCENT WITH A/C YAWING	HEAVY	PARTIAL INFLATION	IMMEDIATE
15	3-2-83	SEA KING	4	1D	–	3N	PILOT ERROR	HIGH FWD SPEED SLIGHT NOSE DOWN IMPACT	LIGHT	NOT USED	IMMEDIATE
16	30-9-82	LYNX	3	–	–	3N	HYDRAULIC FIRE	CONTROLLED DITCHING FROM HOVER	LIGHT	SERVICEABLE	IMMEDIATE
17	11-7-82	SEA KING	4	–	–	4N	ENGINE FAILURE	CONTROLLED DESCENT FROM HOVER	LIGHT	SERVICEABLE	DELAYED
18	19-5-82	SEA KING	30	21D	8	1N	DISORIENTATION??	FLEW INTO SEA ON TAKE-OFF	FLEW IN	NOT USED	IMMEDIATE
19	18-5-82	SEA KING	4	–	–	4N	RAD ALT FAILURE	INADVERTENT DESCENT FROM HOVER	LIGHT	SERVICEABLE	NO
20	12-5-82	SEA KING	4	–	–	4N	ENGINE FAILURE	DESCENT FROM HOVER WITH LTD. CONTROL	LIGHT	NOT USED	IMMEDIATE
21	23-4-82	SEA KING	2	1D	–	1M	DISORIENTATION	INADVERTENT DESCENT FROM HOVER	HEAVY	NOT USED	IMMEDIATE
22	7-10-81	WESSEX	6	–	–	6N	TAIL ROTOR FAILURE	CONTROLLED ENGINE-OFF DITCHING	LIGHT	PARTIAL INFLATION	IMMEDIATE
23	15-7-81	WESSEX	4	–	–	4N	ENGINE FAILURE	VERTICAL DESCENT WITH LIMITED CONTROL	LIGHT	SERVICEABLE	DELAYED
24	11-3-81	WESSEX	3	–	–	3N	ENGINE FAILURE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	DELAYED
25	6-3-81	SEA KING	4	4D	–	–	MID-AIR COLLISION	OUT OF CONTROL	O. OF C.	NOT USED	IMMEDIATE
26	6-3-81	SEA KING	4	1D	(1M, 2N)		MID-AIR COLLISION	UNCONTROLLED DESCENT	HEAVY	PARTIAL INFLATION	IMMEDIATE
27	18-2-81	SEA KING	7	–	(4M, 3N)		TAIL ROTOR FAILURE	DESCENT FROM HOVER WITH A/C YAWING	HEAVY	NOT USED	IMMEDIATE
28	21-1-81	SEA KING	4	–	–	4N	YAW CONTROL FAILURE	CONTROLLED ENGINE-OFF DITCHING	LIGHT	PARTIAL INFLATION	IMMEDIATE
29	27-6-80	WESSEX	3	3I	–	–	ENGINE FAILURE	UNCONTROLLED DESCENT	O. OF C.	NOT USED	IMMEDIATE
30	22-5-80	WESSEX	5	–	–	5N	MRGB OIL FAILURE	CONTROLLED DESCENT FROM HOVER	LIGHT	SERVICEABLE	DELAYED

Table 1: UK Military Helicopter Water Impacts 1971–1992 (continued)

31	14-1-80	SEA KING	5	–	–	5N	MRGB OIL FAILURE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	DELAYED
32	19-4-79	WESSEX	3	–		(2M, 1N)	DISORIENTATION	HIT SEA IN FOG	LIGHT	NOT FITTED	IMMEDIATE
33	20-9-78	WESSEX	4	–	–	4N	ENGINE PROBLEM	CONTROLLED DITCHING	LIGHT	PARTIAL INFLATION	IMMEDIATE
34	13-9-78	WESSEX	3	–	–	3N	GEARBOX FAILURE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	NO
35	25-8-78	SEA KING	7	–	–	7N	MRGB OIL FAILURE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	DELAYED
36	18-7-78	WESSEX	3	–	–	3N	BLADE STRIKE / PE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	NO
37	30-3-78	SEA KING	8	–	–	8N	MRGB OIL FAILURE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	NO
38	25-10-77	SEA KING	4	–	3	1N	TAIL ROTOR FAILURE	DESCENT FROM HOVER WITH A/C YAWING	HEAVY	NOT USED	IMMEDIATE
39	13-12-76	WESSEX	4	1D		(1M, 2N)	LASHINGS NOT REMOVED	UNCONTROLLED IMPACT AFTER TAKE-OFF	O. OF C.	SERVICEABLE	IMMEDIATE
40	11-10-76	WESSEX	2	–	–	2N	ENGINE FAILURE	VERTICAL DESCENT UNDER LTD CONTROL	LIGHT	SERVICEABLE	NO
41	31-3-76	SEA KING	4	–	–	4N	SEVERE VIBRATION	DESCENT FROM HOVER WITH LTD. CONTROL	LIGHT	NOT USED	IMMEDIATE
42	16-1-76	WESSEX	7	–		(2M, 1N)	CONTROL FAILURE	UNCONTROLLED DESCENT AFTER TAKE-OFF	O. OF C.	SERVICEABLE	DELAYED
43	17-11-75	SEA KING	3	–	–	4N	MRGB OIL FAILURE	DESCENT FROM HOVER WITH LTD. CONTROL	LIGHT	NOT USED	IMMEDIATE
44	17-9-75	WESSEX	4	–	–	4N	ENGINE FIRE	– – – – – – – – – –	LIGHT	PARTIAL INFLATION	IMMEDIATE
45	21-8-75	WESSEX	2	–	–	4N	TAIL ROTOR FAILURE	– – – – – – – – – –	LIGHT	SERVICEABLE	NO
46	22-5-75	WESSEX	4	–		(2M, 1N)	ENGINE PROBLEM	– – – – – – – – – –	LIGHT	SERVICEABLE	DELAYED
47	19-3-75	SEA KING	3	–	–	4N	ENGINE FAILURE	DESCENT FROM HOVER WITH LTD. CONTROL	LIGHT	SERVICEABLE	DELAYED
48	12-12-74	SEA KING	6	–	–	5N	SEVERE VIBRATION	CONTROLLED DITCHING	LIGHT	SERVICEABLE	DELAYED
49	19-11-74	SEA KING	3	–	–	4N	TAIL ROTOR FAILURE	DESCENT FROM HOVER WITH A/C YAWING	LIGHT	NOT USED	IMMEDIATE
50	15-7-74	WESSEX	4	–	–	4N	ENGINE FAILURE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	DELAYED
51	19-2-74	WESSEX	3	2D	–	–	COMPUTER FREEZE	FLOWN INTO SEA, HIGH FWD SPEED	FLEW IN	NOT USED	IMMEDIATE
52	16-4-73	WHIRLWIND	4	–	–	3N	ENGINE PROBLEM	– – – – – – – – – –	LIGHT	NOT FITTED	IMMEDIATE
53	13-12-72	WHIRLWIND	2	–	–	3N	ENGINE FAILURE	CONTROLLED DITCHING	LIGHT	NOT FITTED	IMMEDIATE
54	19-9-72	WESSEX	4	–	–	12N	BLADE STRIKE/ PE	CONTROLLED DITCHING	LIGHT	SERVICEABLE	IMMEDIATE
55	19-7-72	WESSEX	4	–	–	4N	ENGINE FAILURE	DESCENT FROM HOVER WITH LTD. CONTROL	LIGHT	SERVICEABLE	NO
56	10-4-72	SEA KING	3	–	–	4N	SEVERE VIBRATION	DESCENT FROM HOVER WITH LTD. CONTROL	LIGHT	NOT USED	IMMEDIATE
57	16-2-72	WESSEX	4	–	2	1N	ENGINE PROBLEM	VERTICAL DESCENT WITH LTD CONTROL	HEAVY	PARTIAL INFLATION	IMMEDIATE
58	31-1-72	SEA KING	30	–	1	5N	ENGINE FAILURE	DESCENT FROM HOVER WITH LTD. CONTROL	HEAVY	SERVICEABLE	DELAYED
59	6-1-72	WESSEX	4	–	–	3N	FIRE WARNING	CONTROLLED DITCHING	LIGHT	SERVICEABLE	NO
60	22-8-71	WHIRLWIND	4	–		(2M, 3N)	FIRE WARNING	CONTROLLED DITCHING	LIGHT	NOT FITTED	IMMEDIATE
61	18-1-71	WHIRLWIND	2	–		(1M, 1N)	ENGINE FAILURE	CONTROLLED DITCHING, LOW FWD SPEED	LIGHT	NOT FITTED	IMMEDIATE

Table 2: UK Military Helicopter Water Impacts Accident Causes and Injury Distribution

		Accidents	*Injuries* *Fatal*	*Serious*
Mechanical Failure:		34 (55·7%)	3 (6·5%)	11
Main Rotor Transmission	7			
Engine	19			
Tail Rotor	7			
Yaw Control	1			
Other System Failure/Fault:		11 (18·0%)	3 (6·5%)	–
Fuel	1			
Fire	4			
Vibration	3			
Electronic/Instrument	3			
Other	2	2	–	–
Pilot Error, Spatial Disorientation: (includes mid-air collisions)	14	14 (22·9%)	40 (86·9%)	9
TOTAL		61	46	20

Table 3: UK Military Helicopter Water Impacts: Impact Severity And Injury Distribution

	Accidents	*Severity*		*Injuries* *Fatal*	*Serious*
Mechanical Failure:	34	Light	27	–	1
		Heavy	6	–	10
		Out of control	1	3	–
Other Failures/Faults:	11	Light	9	–	–
		Fly in	1	2	–
		Out of control	1	–	–
Other:	2	Light	1	–	–
		Out of control	1	1	–
Pilot Error, Spatial Disorientation:	14	Light	5	1	–
		Heavy	3	5	–
		Fly in	5	30	9
		Out of control	1	4	–
TOTAL	61		61	46	20

Table 4: UK Military Helicopter Water Impacts: Impact Type And Injury Distribution

	Accidents	*Injuries* *Fatal*	*Serious*
Controlled Ditching: – low vertical speed – low forward speed	23 (37·7%)	–	–
Vertical Descent: limited control – low/med vertical speed – low/med forward speed – possible roll/pitch/yaw	17 (27·8%)	–	11
Fly In: – high forward/low vertical speed – low forward/vertical speed – possible nose down pitch	8 (13·1%)	34 (73·9%)	9
Uncontrolled: – aircraft out of control	7 (11·4%)	12 (26·0%)	–
Other:	2	–	–
Unknown:	4	–	–
TOTAL	61	46	20

Table 5: UK Military Helicopter Water Impacts: Summary Of Occupant Injuries

61 Water impacts included in analysis (1971–1992)
273 Occupants involved
13 Fatal accidents – 46 Fatalities
38 Drowned
8 Impact injuries
– 2 from blade strike
– 2 seat failures
– 3 catastrophic impact

Survival rate of 83.1%

18 Accidents involved fatal or serious injuries
7 Accidents accounted for 20 serious injuries:
~ 12 spinal compression fractures
– 6 unknown injuries

21·3% of water impacts analysed resulted in fatalities
82·6% of fatalities were the result of drowning (where cause of death was known)
29·5% of water impacts analysed resulted in serious or fatal injuries
60·0% of serious injuries were spinal compression fractures

Table 6: World Civil Helicopter Water Impacts 1971–1992

	DATE	*AIRCRAFT*	*TOTAL ABOARD*	*INJURIES F*	*S*	*M/N*	*CAUSE*	*NOTES*	*FLOTATION*	*INVERSION/ SINKING*
1	4-6-92	BELL 412	8	1	–	–	ENGINE FAILURE	- - - - - - - - - -	- - - - - - -	SANK
2	14-3-92	SA 332	17	11	1	5	PILOT ERROR	FLY IN, INADVERTANT DESCENT	NOT USED	IMMEDIATE
3	30-1-92	BELL 212	3	–	–	3N	MECHANICAL FAILURE	DESCENT UNDER LIMITED CONTROL	- - - - - - -	- - - - -
4	22-11-91	BELL 214	17	–	–	17N	ENGINE FAILURE	CONTROLLED DITCHING	SERVICEABLE	DELAYED
5	26-8-91	BELL 412	13	1D	4	8N	TAIL ROTOR FAILURE	DESCENT UNDER LIMITED CONTROL	PARTIAL INFLATION	IMMEDIATE
6	12-5-91	SA 330	2	–	–	2	PILOT ERROR	FLY IN, HIGH FORWARD SPEED	- - - - - - -	IMMEDIATE
7	5-4-91	S 61	2	–	–	2M	PILOT ERROR	DESCENT WITH LIMITED CONTROL	- - - - - - -	DELAYED
8	13-3-91	SA 330	5	1	–	4	MECHANICAL FAILURE	DESCENT WITH LIMITED CONTROL	- - - - - - -	- - - - -
9	24-2-91	BELL 212	13	9	–	4	MECHANICAL FAILURE	DESCENT WITH LIMITED CONTROL	- - - - - - -	IMMEDIATE
10	6-12-90	SA 332	12	10	2	–	FIRE	- - - - - - - - - -	- - - - - - -	- - - - -
11	25-7-90	S 61	13	4D,2I	4	3	PILOT ERROR	OUT OF CONTROL	NOT USED	IMMEDIATE
12	15-5-90	S 76	10		–	10	FUEL	CONTROLLED DITCHING	- - - - - - -	DELAYED
13	12-3-90	S 58	13	12	1	–	PILOT ERROR	FLY IN, FWD SPEED	- - - - - - -	- - - - -
14	2-11-89	S 70	6	1	–	2M/3N	PILOT ERROR	FLY IN, VERTICAL DESCENT	NOT FITTED	IMMEDIATE
15	5-9-89	BELL 214	4	2D	1	1M	PILOT ERROR	FLY IN, FORWARD SPEED	NOT FITTED	IMMEDIATE
16	22-7-89	S 58	3	–	–	3N	ENGINE FAILURE	CONTROLLED DITCHING	- - - - - - -	- - - - -
17	5-5-89	BELL 212	10	10	–	–	MRGB FAILURE	OUT OF CONTROL	- - - - - - -	- - - - -
18	10-11-88	S 61	13	–	–	13N	MRGB FAILURE	CONTROLLED DITCHING	- - - - - - -	IMMEDIATE
19	17-10-88	S 61	4	–	–	2M/2N	PILOT ERROR	OUT OF CONTROL	NOT USED	IMMEDIATE
20	10-10-88	S 58	2	–	–	2N	ENGINE FAILURE	CONTROLLED DITCHING	- - - - - - -	- - - - -
21	15-7-88	SA 332	18	–	–	18	MRGB FAILURE	CONTROLLED DITCHING	- - - - - - -	DELAYED
22	14-7-88	SA 330	16	1D	1	14N	CONTROL FAILURE	DESCENT WITH LIMITED CONTROL	NOT USED	IMMEDIATE
23	13-7-88	S 61	21	–	–	21	FIRE	CONTROLLED DITCHING	SERVICEABLE	DELAYED
24	13-7-88	S 58	1	–	–	1N	PILOT ERROR	CONTROLLED DITCHING	- - - - - - -	- - - - -
25	28-3-88	BELL 214	15	–	–	15N	MECHANICAL FAILURE	CONTROLLED DITCHING	DAMAGED	DELAYED
26	9-12-87	S 76	10	–	–	10	PILOT ERROR	FLY IN	- - - - - - -	- - - - -
27	7-12-87	BELL 412	2	–	2	–	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	SERVICEABLE	DELAYED
28	17-6-87	S 58	1	–	–	1N	ENGINE FAILURE	CONTROLLED DITCHING	- - - - - - -	DELAYED
29	21-4-87	BELL 205	1	–	–	1N	ENGINE FAILURE	CONTROLLED DITCHING	- - - - - - -	IMMEDIATE
30	10-1-87	S 58	2	–	–	2N	MECHANICAL FAILURE	CONTROLLED DITCHING	- - - - - - -	IMMEDIATE

Table 6: World Civil Helicopter Water Impacts 1971–1992 (continued)

31	29-12-86	SA 330	17	2D	5	10	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	NOT USED	IMMEDIATE
32	6-11-86	CHINOOK	47	45I	2	–	MRGB FAILURE	OUT OF CONTROL	NOT FITTED	IMMEDIATE
33	10-6-86	BELL 205	2	–	–	2N	OTHER FAILURE	DESCENT WITH LIMITED CONTROL	– – – – – – –	DELAYED
34	15-5-86	BELL 214	20	–	–	20	CONTROL FAILURE	CONTROLLED DITCHING	SERVICEABLE	DELAYED
35	5-4-86	S 76	3	–	–	3	PILOT ERROR	FLY IN, VERTICAL IMPACT	– – – – – – –	– – – – –
36	30-1-86	S 58	1	–	–	1N	ENGINE FAILURE	CONTROLLED DITCHING	– – – – – – –	– – – – –
37	28-6-85	S 76	3	–	–	3	– – – – – – – – –	OUT OF CONTROL	– – – – – – –	IMMEDIATE
38	20-4-85	S 58	3	3D	–	–	CONTROL FAILURE	OUT OF CONTROL	– – – – – – –	– – – – –
39	20-3-85	S 61	17	–	–	17	MRGB FAILURE	CONTROLLED DITCHING	– – – – – – –	DELAYED
40	13-3-85	BELL 214	6	6	–	–	PILOT ERROR	FLY IN, FORWARD SPEED	– – – – – – –	SANK
41	10-12-84	S 58	1	–	–	1N	ENGINE FAILURE	CONTROLLED DITCHING	– – – – – – –	SANK
42	20-11-84	BELL 212	2	(1D,1I)		–	PILOT ERROR	FLY IN	NOT USED	IMMEDIATE
43	1-11-84	S 76	5	5	–	–	ENGINE FAILURE	DESCENT WITH LIMITED CONTROL	– – – – – – –	– – – – –
44	22-8-84	S 58	2	1D	–	1	PILOT ERROR	OUT OF CONTROL	FAILED	IMMEDIATE
45	2-5-84	CHINOOK	47	–	–	47	VIBRATION	CONTROLLED DITCHING	NOT FITTED	DELAYED
46	1-5-84	S 76	12	–	–	12	ENGINE FAILURE	CONTROLLED DITCHING	FAILED	IMMEDIATE
47	2-1-84	BELL 212	3	3D	–	–	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	– – – – – – –	IMMEDIATE
48	24-12-83	BELL 212	2	–	1	1	CONTROL FAILURE	OUT OF CONTROL	PARTIAL INFLATION	IMMEDIATE
49	8-11-83	S 76	4	4	–	–	– – – – – – – – –	OUT OF CONTROL	– – – – – – –	– – – – –
50	14-9-83	S 76	5	–	–	3M/2N	CONTROL FAILURE	DESCENT WITH LIMITED CONTROL	PARTIAL INFLATION	DELAYED
51	16-7-83	S 61	26	20D	2	4	PILOT ERROR	FLY IN, FORWARD SPEED	DAMAGED	IMMEDIATE
52	3-7-83	S 55	1	–	–	1N	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	– – – – – – –	– – – – –
53	10-6-83	BELL 212	4	2D	–	2	VIBRATION	DESCENT WITH LIMITED CONTROL	– – – – – – –	IMMEDIATE
54	11-3-83	S 61	17	–	–	17	MAIN ROTOR FAILURE	CONTROLLED DITCHING	SERVICEABLE	DELAYED
55	9-3-83	BELL 212	11	11	–	–	MRGB FAILURE	OUT OF CONTROL	– – – – – – –	– – – – –
56	14-9-82	BELL 212	6	6D	–	–	PILOT ERROR	FLY IN, FORWARD SPEED	NOT USED	SANK
57	25-8-82	BELL 205	5	2	–	2M/1N	PILOT ERROR	FLY IN	– – – – – – –	– – – – –
58	30-4-82	S 76	13	13	–	–	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	– – – – – – –	IMMEDIATE
59	22-4-82	BELL 212	12	2D	–1	9	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	DAMAGED	IMMEDIATE
60	11-2-82	SA 330	10	–	–	10	ENGINE FAILURE	CONTROLLED DITCHING	– – – – – – –	DELAYED
61	22-1-82	S 58	2	–	–	2N	ENGINE FAILURE	CONTROLLED DITCHING	– – – – – – –	– – – – –
62	3-11-81	BELL 212	9	5	–	4	– – – – – – – – –	OUT OF CONTROL	– – – – – – –	– – – – –
63	11-9-81	BELL 212	2	–	–	2	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	– – – – – – –	– – – – –
64	23-8-81	BELL 212	1	–	–	1	ENGINE FAILURE	DESCENT WITH LIMITED CONTROL	SERVICEABLE	IMMEDIATE

Table 6: World Civil Helicopter Water Impacts 1971–1992 (continued)

65	13-8-81	WESSEX	13	13I	–	–	MECHANICAL FAILURE	OUT OF CONTROL	-------	SANK
66	12-8-81	BELL 212	14	1D	2	11	PILOT ERROR	FLY IN, VERTICAL IMPACT	PARTIAL INFLATION	IMMEDIATE
67	25-7-81	BELL 212	4	–	–	4	ENGINE FAILURE	CONTROLLED DITCHING	-------	-----
68	22-7-81	BELL 212	4	–	–	4	ENGINE FAILURE	DESCENT WITH LIMITED CONTROL	-------	SANK
69	10-3-81	SA 330	17	–	–	17	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	SERVICEABLE	SANK
70	22-2-81	S 62	8	2D	5	1	MAIN ROTOR FAILURE	OUT OF CONTROL	DAMAGED	IMMEDIATE
71	31-7-80	S 61	15	–	–	15	MRGB FAILURE	CONTROLLED DITCHING	NOT FITTED	DELAYED
72	18-7-80	S 58	7	5	–	2	MAIN ROTOR FAILURE	OUT OF CONTROL	-------	-----
73	20-3-80	S 76	14	14	–	–	MRGB FAILURE	OUT OF CONTROL	-------	SANK
74	31-7-79	BELL 212	3	–	3	–	PILOT ERROR	DESCENT WITH LIMITED CONTROL	SERVICEABLE	DELAYED
75	26-6-78	S 61	18	18D	–	–	MAIN ROTOR FAILURE	OUT OF CONTROL	-------	IMMEDIATE
76	3-6-78	BELL 212	15	15	–	–	MRGB FAILURE	OUT OF CONTROL	-------	SANK
77	7-5-78	SA 330	5	2	2	1	MRGB FAILURE	OUT OF CONTROL	-------	-----
78	4-4-78	BELL 212	6	3D	–	3	PILOT ERROR	FLY IN	SERVICEABLE	IMMEDIATE
79	8-12-77	SA 330	19	17	1	1	PILOT ERROR	OUT OF CONTROL	-------	IMMEDIATE
80	23-11-77	S 61	12	12	–	–	PILOT ERROR	FLY IN, FORWARD SPEED	-------	-----
81	1-10-77	S 61	3	–	–	3	VIBRATION	CONTROLLED DITCHING	-------	IMMEDIATE
82	23-6-77	BELL 204	2	–	–	2	----------	OUT OF CONTROL	-------	SANK
83	21-5-77	SA 330	10	5	–	5	MECHANICAL FAILURE	OUT OF CONTROL	-------	-----
84	31-7-76	BELL 212	2	–	–	2	PILOT ERROR	FLY IN	-------	SANK
85	24-3-76	S 58	11	6	1	4	CONTROL FAILURE	OUT OF CONTROL	-------	SANK
86	8-3-76	WESSEX	14	–	–	14	ENGINE FAILURE	CONTROLLED DITCHING	-------	-----
87	3-11-75	BELL 212	9	9	–	–	MAIN ROTOR FAILURE	OUT OF CONTROL	-------	SANK
88	29-4-75	S 58	10	4D	–	6	ENGINE FAILURE	CONTROLLED DITCHING	PARTIAL INFLATION	IMMEDIATE
89	26-1-75	S 58	4	–	–	4	PILOT ERROR	FLY IN, FORWARD SPEED	-------	-----
90	28-5-74	S 58	4	–	–	4	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	-------	DELAYED
91	10-5-74	S 61	6	6I	–	–	MAIN ROTOR FAILURE	OUT OF CONTROL	-------	IMMEDIATE
92	22-4-74	S 58	1	–	–	1	ENGINE FAILURE	CONTROLLED DITCHING	-------	-----
93	9-7-73	S 61	17	4D	–	13	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	-------	IMMEDIATE
94	4-4-73	S 61	18	–	–	18	----------	CONTROLLED DITCHING	-------	-----
95	28-2-73	S 55	7	(1D,3I)2		1	MAIN ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	-------	IMMEDIATE
96	25-3-72	S 58	10	–	–	10	TAIL ROTOR FAILURE	DESCENT WITH LIMITED CONTROL	PARTIAL INFLATION	IMMEDIATE
97	17-1-72	S 61	12	–	–	12	ENGINE FAILURE	CONTROLLED DITCHING	-------	DELAYED
98	8-6-71	WESSEX	3	1	2	–	CONTROL FAILURE	OUT OF CONTROL	-------	IMMEDIATE

Table 7: World Civil Helicopter Water Impacts: Accident Causes and Injury Distribution

		Accidents	*Injuries*	
			Fatal	*Serious*
Mechanical Failure:		55 (56·1%)	204 (60·3%)	1124
Main Rotor Transmission	17			
Engine	19			
Tail Rotor	12			
Unspecified mech failure	7			
Other System Failure/Fault:		14 (14·2%)	23 (6·8%)	7
Fuel	1			
Fire	2			
Vibration	3			
Control Failure	7			
Other system	1			
Other/not known	5	5	9	
Pilot Error, Spatial Disorientation:	24	24 (24·4%)	102 (30·1%)	15
	TOTAL	98	338	46

Table 8: World Civil Helicopter Water Impacts: Impact Type And Injury Distribution

		Accidents	*Injuries*	
			Fatal	*Serious*
Controlled Ditching: – low vertical speed – low forward speed		29 (29·5%)	4	–
Vertical Descent: limited control – low/med vertical speed – low/med forward speed – possible roll/pitch/yaw		25 (25·5%)	47	19
Fly In: – high forward/low vertical speed – low forward/vertical speed – possible nose down pitch		17 (17·3%)	78 (23·0%)	7
Uncontrolled: – aircraft out of control		25 (25·5%)	198 (58·5%)	18
Other/Unknown:		2	11	2
	TOTAL	98	338	46

Table 9: World Civil Helicopter Water Impacts: Summary of Occupant Injuries

98 Water impacts included in analysis (1971–1992)
902 Occupants involved
48 Fatal accidents – 338 Fatalities
– 57 crew members
– 281 passengers

Survival rate of 62·5%

In 24 accidents where the cause of death was known:

– 162 fatalities
– 92 drowned

52 Accidents involved fatal or serious injuries
22 Accidents accounted for 46 serious injuries:
~ 14 crew members
– 32 passengers

48·9% of water impacts analysed resulted in fatalities
56·7% of fatalities were the result of drowning (where cause of death was known)
53·0% of water impacts analysed resulted in serious or fatal injuries
Out of 52 accidents that involved serious or fatal injury, 12 (23·0%) resulted in substantial damage to or failure of seats.

Study II

An Analysis of the Response of Helicopter Structures to Water Impact

Summary

The objective of this study was to investigate the response of helicopter structures to impact with water and to examine design techniques to improve occupant survival in these accidents. Three impact categories, controlled ditching, limited control descent and fly-in accidents were identified in an earlier study of UK military and world civil helicopter water impacts over the period 1971–1992. Analyses of these categories were carried out to identify impact parameters and the extent and mechanisms of structural damage.

Impact severity and the probability of occupants surviving an impact with water were found to be dependent on both water impact velocity and the response of the structure on entry into water. It was the water pressures generated on impact rather than the inertia loads that determined this response. The ability of the lower fuselage to withstand these water pressures was the key to survival.

Drowning was found to be the major cause of fatalities in helicopter water impacts. Fatalities due to excessive crash forces or collapse of the structure on impact were of secondary significance. Designing the airframe to remain afloat after impact for long enough for the occupants to evacuate was considered to be a primary objective if occupant survival in water impacts is to be improved.

Contents

1 INTRODUCTION

The crash impact characteristics of aircraft structures has been the subject of numerous investigations over the last three decades. Studies initiated in the US in the 1960's to examine the relationship between crash forces, aircraft structural behaviour and occupant injuries, for example, have resulted in the publication of a series of aircraft crash survival design guides since 1967 (e.g. see Reference 1). From this work, the US Army crashworthiness requirement MIL-STD-1290 has been developed. More recently, analytical techniques including the computer programs KRASH and DYNA3D have become available enabling aircraft designers to calculate crash forces and analyse structural behaviour in dynamic impact environments.

Much of this crash dynamics research, however, has been limited to aircraft land impacts and for analysis purposes has considered impact surfaces to be rigid. Although ground impacts account for the majority of helicopter accidents, collision with water has been identified as a significant accident category. It has been demonstrated that over 24% of world civil helicopter accidents involve collision with water (2). Similarly, 27% of UK military (3) and over 40% of US navy helicopter accidents (4) have resulted in impacts with water.

Information from early investigations has indicated that the response of aircraft structures to water impact is significantly different from that of ground impacts (5). The severity of impact has been shown to be dependent on both impact velocity and behaviour of the aircraft on entry into water and that it is the resulting water pressures rather than inertia forces that ultimately determine the structural response to impact.

The objective of this current work is to investigate the response of helicopter structures to impact with water and to examine design techniques to reduce impact severity and improve occupant survivability in these accidents.

2 A DISCUSSION OF THE AIRCRAFT WATER IMPACT ENVIRONMENT

The significance of water as an impact terrain was recognised by Glancy (6) in a study of US navy helicopter accidents in 1971. For accidents involving impact with water, 95% of fatalities were found to be due not to impact forces but the result of post crash survival issues. Over 54% of occupant fatalities were the result of drowning with a further 38% being lost at sea, presumed drowned; only 2 deaths out of a total of 42 were directly attributable to impact forces. Similar findings as to the primary cause of death in helicopter water impacts have been shown by Vyrnwy – Jones (7), Rice and Greear (8) and Clifford (3).

Two main factors contribute to the large number of fatalities through drowning in helicopter water impacts. Firstly, injuries to legs, arms and head caused by the occupant striking adjacent structure within the aircraft which, although not life threatening, result in incapacitation or delayed egress and can ultimately lead to drowning. The second factor is the tendency for the aircraft to invert or sink on contact with water; the associated inrush of water can produce disorientation and difficulties in exiting the aircraft. It has been shown that in the majority of civil and military helicopter water impacts the aircraft inverts or sinks before occupant evacuation has been completed (3,9). Hence a large number of occupants would have been required to attempt some form of underwater escape. A detailed account of occupant escape and survival from helicopters ditching in water has been reviewed by Brooks (10).

The type of injuries to the body extremities described above are referred to as contact or secondary injuries and form the major class of injuries to helicopter occupants in both land impacts (11) and water impacts (6). The second most significant class of injuries to occupants in land impacts has been identified by Shanahan (11) as acceleration injuries where injury is due to the inertial response of the body to the applied acceleration. That is, crash forces in excess of human tolerance are transmitted through the aircraft structure and seats to the occupant.

In a study of US civil helicopter accidents (12), it was shown that excluding the hazard of post crash fire, the area where the most significant improvement in occupant safety could be achieved was occupant restraint to prevent secondary impacts to the upper torso and head. A study of US navy helicopter accidents by Coltman (4) concluded that the most serious crash hazard resulted from structural failure of crew and troop seats. The primary injury resulting from these failures occurred when the body struck adjacent aircraft structure. Exposing the body to excessive decelerative forces ranked as the second most significant injury type.

Although the primary injury mechanisms, as discussed above, are similar for land and water impacts, significant differences exist in injury patterns that reflect the different nature of the impact terrain. Firstly, spinal injuries (invariably compression fractures) are more frequent in helicopter water impacts, due in part to the absence of energy absorption contributions from the landing gear (3). Secondly, whereas impact forces are the primary cause of fatalities in land impacts, these forces account for relatively few deaths in water impacts (6). The relatively few number of acceleration or impact force fatalities in water impacts would appear to indicate lower crash forces in this type of accident.

A review of occupant injuries in fixed wing aircraft water impacts by Snyder (13), makes an interesting comparison with the work reviewed above. A study of large US passenger transport aircraft accidents revealed that 89% of fatalities were due to impact forces and only 71 occupants died as a result of drowning or other post impact cause. An analysis of light aircraft ditchings, however, found that at least 50% of fatalities were due to drowning. This study reported that occupants of high wing multi-engined light aircraft had a significantly less chance of surviving a water impact than other aircraft configurations. Aircraft size and configuration was, therefore, shown to have a significant influence on the survivability of water impacts and the type of occupant injuries. It was also concluded that in general, water impacts were more survivable than land impacts when the two criteria, magnitude of crash forces and maintenance of a protective shell for occupants, were considered.

Aircraft structural design criteria to protect occupants in potentially survivable accidents have been developed through numerous crashworthiness research programmes in the US (see for example reference 1) and are now well understood. It is recognised, for example, that the primary objectives of crashworthiness design are to maintain airframe structural integrity, that is a protective shell for occupants, and to limit decelerative forces transmitted to the occupants to within human tolerance limits by providing energy absorbing structure and systems. Kinematic studies of helicopter crashes have shown that vertical impacts are the most severe accident type (11, 12, 14). For these impacts, where the impact surface is rigid, crash energies can be absorbed through the landing gear, underfloor structure and seats. Keel beams and bulkheads in the underfloor structure can be designed to react to impact loads and absorb energy by controlled collapse. In impacts on soft ground, the undercarriage will be less effective due to wheels or skids penetrating the surface, although this can be offset by increased energy absorption as the airframe structure deforms and compacts the soft surface.

Vertical impacts onto water, however, will not receive any benefit from the energy absorption capability of the landing gear as the water surface will offer little resistance to penetration. In addition, impact forces will be reacted by those areas of the airframe having the largest surface area resulting in possible rupture of the lower fuselage skin panels and little energy absorbing deformation of the primary load paths. Thus, the type of impact surface can significantly affect the behaviour and energy absorption performance of the lower fuselage and can determine the scale of occupant injuries.

For forward speed impacts onto water, e.g. fly-in impacts, the response of the aircraft is dependent on the resistance to forward motion through the water. A low drag structure will, for example, generate lower fore-aft deceleration loads than one with a higher resistance. The ability of the aircraft to hydroplane, thereby allowing part of the structure to rise out of the water, will also reduce fore-aft decelerations by reducing the area of the structure in contact with the water. The response of the aircraft is also dependent on the integrity of the forward and lower fuselage. Any structural distortion or failure of this structure that results in increased drag, will generate higher fore-aft deceleration loads in the lower fuselage as the aircraft moves through the water. Increased loads in the lower fuselage can lead to greater structural distortion and failure and further increases in drag. The result of these rapidly increasing loads can lead to catastrophic destruction of the forward fuselage and break up of the airframe. The mechanisms of these structural failures have been discussed by Clifford in Reference 5. The response of aircraft structures to impact with water can, therefore, be shown to be highly dependent on structural shape and geometry and the integrity of the lower fuselage panels. These criteria, however, are not generally considered in crashworthiness design.

The behaviour of structures discussed above can be attributed to the mechanism of crash force generation and distribution. In impacts against a solid surface, impact forces are generated as a result of the inertial response of high mass items. These inertial loads are distributed through the high stiffness primary load paths in the airframe. Crash forces (i.e. decelerative loads) are therefore a function of the stiffness of the structure. In water impacts, it is the application of water pressures against the outer profile of the fuselage that generate impact forces. These forces are a function of the area of the structure in contact with the water and the degree of resistance to movement through the water. The response of structures to impact with water and the factors that control this response are discussed in more detail in Section 4.

As discussed earlier, water impacts can be more severe than equivalent land impacts in that they result in a higher proportion of spinal injuries. However, whereas high impact velocities result in fatal crash force injuries to occupants in land impacts, in water impacts drowning is the primary cause of loss of life. This result is believed to be due to the greater tendency for the aircraft to break up on contact with water (20).

As will be discussed in Section 4, crash forces are generally lower in water impacts than in equivalent velocity land impacts. It is the mechanism by which these forces are applied to and reacted by the structure that accounts for the greater levels of structural damage in aircraft water impacts.

3 REVIEW OF WATER IMPACT ACCIDENT DATA

3.1 Accident Classification

UK military and world civil helicopter accidents involving impact with water have been reviewed in Reference 3 for the period 1971–1992. Although a statistical analysis of accident data to determine impact velocities and aircraft attitudes was not included in this review due to lack of data, it was found that approximately 70% of water impact occurrences could be categorized into 3 impact types for which typical impact conditions could be identified. These impact categories were identified as controlled ditching, vertical descent with limited control and fly-in impacts. The majority of the remaining 30% of water impacts were either determined to be out of control accidents or of an unknown cause. For each impact category the following impact conditions were identified:

(a) *Controlled Ditching*

A controlled ditching generally involves forward speed below 20 Kts and a vertical velocity of less than 10 ft/s. Forward speeds in the region of 20 Kts were associated with autorotative landings resulting from partial or total loss of power. Aircraft pitch was usually in the range 0–5° nose up; again the higher pitch angles were associated with autorotative landings. As the aircraft would be under full control, roll attitudes were generally level and yaw angles minimal.

(b) *Vertical Descent with Limited Control*

In this impact category, forward speeds were generally in the range 0–70 Kts with vertical velocities up to 25 ft/s. Aircraft attitudes were not as well controlled as the previous category and pitch angles in the range $\pm 10°$ and roll angles between $\pm 20°$ were typical. Because this category includes accidents involving loss of tail rotor control, yaw angles on contact with water may be significant. Higher impact speeds than category (a) were generally the result of either tail rotor failure or a loss of power in circumstances where a successful autorotation was not possible (e.g. low altitude).

(c) *Fly-In Accidents*

Accidents in this category were invariably the result of pilot error or disorientation and were high forward speed shallow angle impacts with a water surface. Forward speeds were typically up to 100 Kts with aircraft pitch attitudes in the range 0–5° nose down. Because the aircraft was likely to have been in controlled forward flight, with the pilot unaware of an impending accident, vertical impact velocities were low and generally below 10 ft/s.

One of the primary objectives of aircraft accident investigation and accident data analysis is the definition of impact parameters such as impact velocity and aircraft attitude. This information is essential in evaluating the level of crashworthiness in current helicopter designs and in establishing future crashworthiness design criteria. As noted previously, a discussion on impact parameters was not included in the accident data review in Reference 3 due to the lack of information in the original accident reports. In previous reviews of US navy (4) and US civil (12) helicopter accidents, accident reconstruction techniques were frequently used to determine impact parameters. The resources required to undertake such a task were viewed as too prohibitive to be considered in this current study.

One additional accident not covered by the above three categories is considered worthy of inclusion because of the nature of the accident and the level of detail recorded during the accident investigation. The accident in question was a civil S61N helicopter (G-BEWL) that crashed into the sea from the North Sea oil platform Brent Spar on 25th July 1990. The aircraft hit the sea with a vertical velocity of 70–80 ft/s in a 5–10° nose down attitude and rolled 10° to starboard. This accident is reviewed in Section 5.

3.2 Structural Damage Following Water Impact

The extent and magnitude of structural damage to helicopters in the water impacts described in Reference 3 are discussed below for the three impact categories.

(a) *Controlled Ditching*

As a result of the low velocities and near level impact attitude, damage in this category is limited to minor water forming of lower fuselage panels and failure or disruption of low strength fairings and access panels. Impact conditions are well within the structural capability of the airframe. However, although the aircraft may be under full control, limiting the descent velocity to the design criteria for flotation systems was in some cases unsuccessful. Current BCAR requirements specify that rotorcraft, together with equipment fitted for emergency alighting on water shall be designed for vertical impact velocities of 1·5 m/s and a forward speed equal to ⅔ of the best autorotational descent speed (16). As a result of descent rates commonly exceeding 1·5 m/s (5 ft/s), damage to flotation systems was frequently encountered resulting in helicopter inversion or sinking.

Although impacts with a water surface were generally classed as light to firm in this category, deceleration levels in excess of 4½g have been recorded for fully controlled ditchings based on the incidence of crash inertia switches (set to trip at 4½g on the Wessex helicopter), firing on contact with the water surface. It has also been shown in helicopter model drop tests that vertical descent rates representative of a well controlled alighting onto water, e.g. 3 ft/s, can produce vertical decelerations in the range 4–6g for an aircraft in a level attitude. It should be noted that the inertia forces required by BCAR to be considered in the design of helicopters for 'Emergency Alighting' include a 6g vertical downwards case (17).

Although a ditching may be well controlled, the structural response of the aircraft will be dependent on sea state conditions. For example, a Lynx helicopter undergoing a controlled power on ditching from a 20 ft hover (accident 16 in Table 1 of Reference 3) suffered a tail cone fracture at the transport joint attributed to wave damage. Although the flotation system operated successfully the aircraft remained afloat for less than one minute in conditions of sea state 5–6.

In another example of a controlled ditching, accident 33 in Table 1 of Reference 3, a Wessex helicopter suffered an engine failure in an 80 ft hover. The pilot flared the aircraft and had the collective fully raised just before impact. The aircraft hit the sea in a tail down attitude with a forward speed of approximately 10 Kts. The airframe sustained minor water forming and buckling of the forward nose structure suggesting a low forward speed at impact. The underside of the fuselage had slight water forming damage. The flotation system, however, only partially inflated and the aircraft immediately inverted.

(b) *Vertical Descent with Limited Control*

The higher impact velocities coupled with lower levels of control in this impact category produced more extensive water forming of lower fuselage structure than the previous category. Structural failures of a low to moderate severity may be evident but airframe structural integrity is not compromised. These failures may include failure of fuselage longitudinal members in bending or shear as the water surface provides a non-uniform support to the aircraft during the impact. Seat and floor distortion may also occur for the more severe impacts although seat failures are rare.

Impacts in this category invariably result in failure of the tailcone or rear fuselage. Failure of lower forward fuselage panels and structure in some aircraft may allow an inrush of water to cockpit and cabin areas that present additional hazards to occupants. For the military Sea King helicopter, a number of accidents involving forward speed have resulted in the electronics bay door located in the nose of the aircraft failing under water pressure loads. An example of a limited control impact to a Canadian S61 helicopter in which the electronics bay door has been torn away is shown in Figure 1. Damage to flotation systems is more frequent than for controlled ditching and total system failures are not uncommon as a result of local structural deformation and failures. Following an accident to a Bell 212 (accident 66 in Table 6 of Reference 3), two recommendations relating to flotation equipment were made in the Air Accidents Investigation Branch Aircraft Accident Report (18). It was recommended that the adequacy of the 1·5 m/s vertical descent rate required by the BCARs, covering the strength of emergency flotation equipment, be reviewed. Secondly, that the flexible pipes on emergency flotation equipment be modified to permit a greater degree of structural distortion before failure.

The magnitude of crash forces in this impact category vary but vertical decelerations at crew stations are generally in the range 5–25G based on the occurrence of spinal injury. Tail rotor failures are a frequent occurrence in this category. The significant aircraft yaw rates that may result from these failures often produce a lateral displacement of the occupants upper torso due to centrifugal forces. These displacements can lower the tolerance of the spine to compression loads and hence increase the probability of spinal injury (19).

One example of an impact in this category is accident number 14 in Table 1 of Reference 3. In this accident following a tail rotor failure, the aircraft hit the sea with a low forward speed in a nose down attitude and with a high rate of yaw. Although the water impact was cushioned by use of the collective, the impact was classed as severe with vertical decelerations calculated to be in the region of 18–22g. The lower fuselage sustained substantial damage and all four occupants received spinal injuries.

In another example (accident number 57 in Table 1 of Reference 3), a Wessex helicopter made a controlled autorotative landing following an engine failure. Just prior to impact, the collective was fully raised to cushion the impact. The landing, however, was made on the crest of a wave and two rear cabin occupants, sitting in the area that faced the brunt of the impact and sustained severe distortion, received spinal injuries.

(c) *Fly-In Impacts*

These accidents are generally high forward speed shallow impacts onto water with relatively low vertical velocities. Damage to the forward and lower fuselage is likely to be extensive but will ultimately depend on the ability of the structure to withstand high water pressures. If the structure in contact with water can withstand the applied water pressures and offer a low drag profile, longitudinal decelerations may be relatively low. In this case aircraft kinetic energy would be attenuated through forward motion of the aircraft in the water. In the majority of cases, however, outer skins of the forward and lower structure collapse and fail under the applied water pressures.

As these failures may expose further surfaces to contact with the water, in particular vertical bulkheads and internal frames, drag forces may increase further producing further structural failures. This progressive mechanism of load increase and structural collapse may ultimately result in catastrophic break up of the airframe in high forward speed impacts.

High water pressure loads are only generated in the localised areas of the airframe in direct contact with the water surface. As a result, major structural failures may occur even though the deceleration loads on the airframe remote from the point of water contact are within the capability of the airframe. Catastrophic failures of the airframe with the occupants surviving the initial impact are not uncommon. However, it is structural damage caused by the high water pressure loads that contribute to the high incidence of drowning in these accidents by, for example, entrapping occupants and jamming exits in aircraft that subsequently invert or sink. Collapse of cockpit and forward fuselage structure in survivable accidents has been shown to be a significant hazard in forward speed impacts (3, 6, 10).

An example of the effect of water pressure loads during high forward speed fly-in impacts is the account of accident number 6 in Table 1 in Reference 3. In this UK navy Sea King accident, water pressures generated by an inrush of water in the lower fuselage following failure of the electronics nose bay door, produced an upward bending failure of the cockpit floor. Cockpit seats, containing restrained crew members, together with sections of the cockpit floor were then projected forward out of the cockpit as the aircraft decelerated.

Although impact forces are generally not severe, it has been shown that major structural failures can occur in forward speed shallow angle impacts at speeds as low as 28 Kts. Because of the nature of water as an impact surface and the mechanism of hydrodynamic forces, loads initiating these structural failures may be generated by water pressures as low as 3 lb/in^2. A more detailed description of aircraft structural damage for specific water impacts is given in Section 5 of this report.

4 A REVIEW OF PREVIOUS AIRCRAFT WATER IMPACT STUDIES

4.1 Vertical Impacts

The response of helicopter structures to vertical impact onto various surfaces has been reviewed by Wittlin (15, 21), Cronkhite (14) and Schultz (22). As discussed earlier, the type of impact surface has been shown to have a significant effect on the distribution of impact loads through the structure. For an impact against a solid surface, loads are distributed through the high stiffness structural elements such as underfloor keel beams and bulkheads. As the loading is concentrated, these elements are highly loaded and can be designed to crush progressively to absorb energy. For a water impact, however, the structure is exposed to fundamentally different impact loading as shown in Figure 2. Loads are distributed over a large area of the lower surface, that is, the area of the fuselage in contact with water and thus the skin panels become highly loaded. Under severe hydrodynamic loads these skin panels can fail between the beams and bulkheads and prevent these elements from crushing and absorbing energy.

As deformation and failure of these panels involve little energy absorption, higher initial loads are transmitted through the structure to occupants and the upper fuselage. Furthermore, on failure of these panels, internal surfaces such as fuel tank structure and high stiffness floor panels are then exposed to the water surface. The high speed contact between these large flat areas and the inrushing water can generate high impact forces and result in high structural deceleration levels. In some cases, upward moving columns of water may disrupt floor areas and lead to distortion of seat attachments (22).

As described in 3.2, vertical impacts onto water can result in bending and shear failure of the lower fuselage. This occurs due to the water surface being unable to fully support the aircraft along its length. Certain areas of the fuselage, for example, may penetrate the water surface with less resistance than other areas. From a KRASH analysis of a vertical impact in Reference 5, Figure 3 shows typical lower fuselage deformation. This predicted mode of failure compares well with the accident to a navy Lynx helicopter shown in Figure 9.

A considerable amount of theoretical and experimental research has been conducted to determine the magnitude and distribution of water pressures on structures during water planing and landing. Most of the theories have been based on the concept that during impact, the momentum lost by the impacting body could be considered to be transferred to a finite mass of water in contact with it and having the same velocity. This mass of water is generally referred to as the virtual mass. From a review of early impact and planing theories by Smiley (23), the dynamic pressure acting on a surface in contact with water can be expressed by the functional relationship:

$$P = \tfrac{1}{2}\rho V^2 . \text{ function of } (\beta\gamma\ \lambda b)$$

Where
- ρ = fluid density
- V = equivalent planing velocity ($V = Vx + Vy \cot\gamma$)
- β = included angle of a V shaped hull
- γ = angle of impact surface relative to the water surface
- λ, b = parameters defining the area of the wetted surface
- Vx = velocity of impact surface parallel to water surface
- Vy = velocity of impact surface normal to water surface

Specific theories of water planing and impact including the pioneering work of Von Karman and Wagner are discussed in Reference 24.

Although these early theories were based on a relatively simple 2D treatment of water impact, they were nevertheless found to be in good agreement with experimental data and formed the basis of early seaplane and float design (25). Of more importance to this present work, however, was the understanding that impact forces were dependent on the geometry of the surface contacting the water and the angle of impact and were not simply a function of impact velocity.

Later studies on hydrodynamic impact considered the response of 3D structures to impact with water. Hagiwara and Yuhara, for example, carried out drop tests of large 3D semi-cylindrical models with different radii and different relative angles between the model and the water surface (26). Results of these tests have shown that impact pressures were strongly dependent on relative angle. Increasing the impact angle from 0° to 15°, for example, reduced pressures from 400 lb/in^2 to 44 lb/in^2. A similar effect has been reported by Mayo (27). Increased relative angles between a prismatic float and the water surface were shown to lower the rate of increase of the virtual mass for a specific vertical velocity thus resulting in lower impact forces.

Recent developments of the crash analysis computer program KRASH have included the capability for analysing water impacts. In the DRI/KRASH-PC version of the program, algorithms are now included based on the hybrid hydrodynamic theory developed by Collopy (28). Using this program, Wittlin (29) has studied the effect of structural geometry on the response of solid surfaces to water impact. Increasing the diameter of a sphere from 3ft to 4ft increased deceleration levels from 10g to over 14g for a 30 ft/s vertical impact. In an analysis of a cone configuration, increasing the included angle of the cone from a sharp 90° to a less sharp 140°, resulted in an increase in vertical deceleration from 6g to 16g for the 30 ft/s impact. The results of this study are summarised in Figure 4.

In a NASA study of the water landing characteristics of a re-entry capsule, the angle of water entry was again shown to have a significant effect on deceleration levels (30). Data from model tests have shown that vertical decelerations are reduced from 40g to 7·6g when the attitude at contact with water is increased from 0° to 33° in a 30 ft/s vertical impact. Model geometry and a summary of results are shown in Figure 5. The experimental and analytical data discussed above have been generated using rigid body models. The work described in Reference 31 has shown that flexible structures, built to a representative stiffness, generate considerably higher forces and decelerations than rigid vehicles.

Model drop tests of representative helicopter structures have again shown the dependence of structural shape and impact angle on deceleration loads. Unfortunately this data has not been published. From other studies a model of a small flat bottomed helicopter (7000 lb AUW) dropped vertically at 3 ft/s generated deceleration levels in the vertical direction in the range 4–6g for a level attitude impact. When the model was orientated so that impact occurred at 5° pitch, decelerations were reduced to 2–4g. By comparison, a large helicopter (20,500 lb AUW) with a V-bottomed hull when dropped in a level attitude at 10 ft/s only generated a vertical deceleration of 3·9g.

These results go to some length to possibly explain why impact severity and injury probability are difficult to estimate from impact velocity alone. The North Sea Brent

Spar accident (accident number 11 in Table 6 of Reference 3) is a good example. In this accident a civil S61N helicopter fell out of control from an oil rig platform and hit the sea, 105 ft below, at 70–80 ft/s. Had this impact occurred on land, the accident would have certainly not been survivable. From Reference 12, the 95th percentile potentially survivable vertical impact velocity is 26 ft/s for civil helicopters; the corresponding figure for military helicopters is 42 ft/s (32). The fact that there were no fatal injuries resulting from impact forces in this accident was undoubtedly due to the 10° nose down pitch and 10° roll angle of the helicopter on impact with the water surface. In the Air Accidents Investigation Branch accident report for the Brent Spar accident (33) peak deceleration loads at the cabin floor were calculated to be in the range 20–25g. In comparison, a cockpit floor deceleration of 18–22g was calculated for a military Lynx helicopter that hit the sea during a vertical descent under limited control following a tail rotor failure. It is clear from the evidence reviewed above that the response of helicopters to a vertical impact with water will be highly dependent on aircraft design (i.e. shape and construction of lower fuselage) and the angle of entry into water.

4.2 Longitudinal Impacts

The response of aircraft structures to longitudinal or forward impacts with water has been reviewed by Wittlin (15, 21) and Johnson (20). As discussed earlier, the response of aircraft structures can be highly dependent on the integrity of the lower and forward fuselage structure. If this structure remains essentially intact without excessive deformation, the aircraft may continue forward motion through the water with a relatively low longitudinal deceleration. However, failure or damage to those areas of the aircraft in contact with water will significantly increase the drag resistance to forward motion with a corresponding increase in aircraft longitudinal decelerations. Failure of panels that allow water to contact internal structural surfaces, such as vertical beams and bulkheads, will result in further significant increases in drag force. This drag force will increase as the area of exposed structure increases. High drag forces are applied to the lower forward structure and are opposed by the inertial loads associated with the high mass items located in the upper fuselage. This effect will induce a nose down pitching moment which may increase the area of the structure in contact with the water and thus increase drag forces. A similar effect can result from immersion of exposed undercarriage legs or skids in the water surface.

Drag or contact forces are only applied to those areas of the structure directly in contact with the water surface and thus the area involved will initially be relatively small. This concentration of loads may produce localised collapse of the forward structure even though the average airframe decelerations are low. The hazard of cockpit structure collapsing and trapping crew members in their seats in forward speed water impacts has been identified by Glancy (6). In 3 of 9 Sikorsky US Navy S61 helicopter water impacts in the period 1969–1971, the pilot or co-pilot, or both, were ejected through the windshield in longitudinal impacts while still restrained in their seats. In one further case the pilot, although his seat came loose from the aircraft, was not thrown out because the nose compartment rolled up on impact and trapped his legs. This mechanism was also considered to be a significant cause of drowning in the review of accident data in Reference 3.

In another accident reviewed by Brooks (10), a US Naval CH-46 Sea Knight helicopter impacted the water after take-off from a ship. The helicopter was noted to never gain more than about 90 feet of altitude. It made an essentially wings level descent into the water, rolling to port on impact and sinking immediately. Two crew and thirteen passengers died; the co-pilot and one passenger suffered major injuries. Impact forces ripped the cockpit section from the rest of the aircraft. The co-pilot still strapped in his seat was thrown out of the aircraft as it came to rest. He inflated his life preserver and was carried to the surface.

A structure moving through water with a forward velocity will generate hydrodynamic planing pressures according to the relationship described in 4.1. Smiley (23) has shown that this relationship holds true for both planing and impact in water.

In addition to these forces associated with momentum exchange, movement of a surface through water will generate a drag force according to the relationship.

$F = \frac{1}{2}\rho Vx^2.A.CD$

Where Vx = velocity normal to the surface
A = area of the surface
CD = drag coefficient
ρ = density of fluid

As described in 4.1, forces or pressures generated on contact with water are again strongly dependent on structural geometry and angle of contact with the water surface. For the impact of prismatic surfaces onto water, Mayo (27) has identified the roles played by planing and impact forces in controlling the response of structures. For small flight path angles, i.e. shallow angle impacts, the planing force predominates and the effect of increased pitch angle increases the resultant force and makes the impact more severe than for a small pitch angle. For large flight path angles, however, the increase of the virtual mass due to the vertical velocity dominates the impact force. Increased pitch will lower the rate of increase of the virtual mass for a specific vertical velocity and hence a less severe impact than for a small pitch angle will occur.

A similar relationship between pitch angle and impact forces has been demonstrated in scale model ditching tests of fixed wing aircraft. A NASA study into the ditching characteristics of a large jet transport airplane demonstrated that the most favourable condition for ditching was a 7° landing attitude at 137 Kts (34). Deceleration levels in this case were 3·5g maximum longitudinal deceleration and 6g maximum vertical deceleration. In a 12° attitude, the rear section of the scale strength fuselage was damaged and this damage allowed the bulkheads in this area to produce large drag loads on contact with the water and caused the aircraft to pitch nose down. When the nose section impacted the water, a 17g peak vertical deceleration occurred and the front section of the scale strength fuselage sustained considerable damage.

Data from a number of scale model ditching trials have also demonstrated the effect of aircraft attitude on structural behaviour. Over the range of forward speeds 20–45 Kts and at a 5 ft/s rate of descent, a 16,000 lb transport helicopter generated the lowest forward deceleration at a pitch attitude of 8°; attitudes of 5° and 12° generated higher decelerations. Longitudinal decelerations were typically 1g at the lower speeds and 1·5–2·0g at the higher speed range. Vertical decelerations showed little or no relationship with forward velocity. For the forward speeds of 20, 30, 40 and 45 Kts, aircraft vertical decelerations were 2·5g, 3·9g, 3·7g and 3·3g respectively for the 8° pitch case.

The effect of fuselage bottom strength on ditching behaviour was also investigated in Reference (34). Results showed that for a range of impact speeds, 126–162 Kts, and pitch angles 7–12°, longitudinal decelerations generated in the ditching of a large jet transport airplane were higher for the high strength bottom structure although the difference was insignificant. This high strength structure was approximately twice the strength of the production structure. However, for the vertical case the standard strength structure, i.e. production standard, produced decelerations 20% higher than for the high strength structure. The most significant difference in performance was for the high pitch angles. It was also noted that aircraft nose down pitch accelerations were considerably lower for the high strength floor. This behaviour was attributed to the greater levels of damage and hence higher drag from the lower strength floor.

A series of scale model ditching trials on a small naval helicopter with hatches removed to simulate failure of low strength panels has shown similar behaviour to that discussed above. At a forward speed of 12 Kts and a rate of descent of 3 ft/s, vertical decelerations measured at the aircraft c.g. were found to be 22% higher when the hatches were removed, i.e. 2·2g compared to 1·8g for tests with hatches in place.

Model tests described in Reference 35 and shown in Figure 6 demonstrate a much more significant effect of damage to the lower fuselage of fixed wing aircraft. The introduction of damaged regions to the lower fuselage and the removal of parts to represent the failures of low strength access panels and underfloor bay doors increased longitudinal decelerations by nearly a factor of 2 (i.e. 3½g to 6g) for transport aircraft and by a factor of 3–10 for a fighter aircraft.

In a study of large transport fixed-wing aircraft water impacts, Johnson (20) has shown that the probability of occupant survivability decreases as the level of major structural damage to the aircraft increases. Water impacts involving ruptured lower surfaces of the fuselage but without fuselage breaks accounted for 3 of the 11 accidents investigated; all these accidents were fatal with 18·1% of occupants losing their lives. These impacts resulted in significant floor distortion due to the hydrodynamic forces of water entering the fuselage through breaks in the underside of the fuselage. This distortion frequently resulted in displacement and elevation of floor beams with subsequent separation of seats.

In accidents where the fuselage broke into several sections (6 of the 11 cases reviewed) all cases were again fatal but here 36·8% of occupants were fatally injured. Of the 217 occupants who drowned in water impacts, over 82% drowned in accidents involving breaks in the fuselage. It was therefore concluded that in water impacts in which the fuselage does not break but remains intact without significant rupture or leakage, the probability of occupant survival is significantly improved.

5 DETAILED REVIEW OF STRUCTURAL DAMAGE TO HELICOPTERS INVOLVED IN WATER IMPACT ACCIDENTS

Information on structural damage to helicopter airframes following impact with water was found to be severely limited. Before 1980, aircraft accident reports rarely contained information on structural damage apart from statements of the form '... airframe sustained substantial damage', and therefore, were of little value to this study. In a number of instances the aircraft sank after impact, with the wreckage not being recovered. Reporting on structural damage to these aircraft was clearly not possible. The information contained in this section is considered to be the best available from the sources consulted.

5.1 Controlled Ditching

Over 37% of UK military and 29% of world civil helicopter water impacts reviewed in Reference 3 were controlled ditchings. A significant number of these accidents involved no discernable damage to the airframe and as such were of little interest to this study.

(a) *Accident A:* Royal Navy Sea King, 21.1.1981

A Royal Navy Sea King helicopter made a well controlled engine off autorotation onto a calm sea following a yaw control problem (accident 28 in Table 1 of Reference 3). Inertia in the rotor system was used to cushion the impact and achieve a near zero sink rate. The tail wheel entered the water with the aircraft travelling at approximately 20 Kts and in a 4° nose up attitude. The drag of the tail wheel slowed the aircraft and at about 10 kts the nose up attitude could not be maintained and the nose of the helicopter entered the water. Once level in the water, the aircraft stopped rapidly and without any tendency to pitch forward. A considerable amount of water was at this stage entering the cockpit as a result of the electronics equipment bay door in the lower nose of the helicopter having been torn away. As the aircraft came to rest, it immediately rolled rapidly to port as a main rotor blade struck the water. The pilot fired the flotation inflation mechanism but due to a malfunction in the firing button only the port bag inflated.

The aircraft suffered impact damage to the lower nose structure through minor water forming of panels. In the forward lower fuselage, damage was confined to an area below the cockpit floor, where the outer skins were dented and torn. There was no obvious damage to the main cabin area or the hull. Seats, seat attachments and occupant restraint systems were all undamaged. The port sponson and the port underside of the tail cone suffered minor skin panel denting. None of the canopy windows were broken. No injuries to the occupants were reported.

Damage to the underfloor and nose structure of this aircraft, including the loss of the nose bay door, is shown in Figures 7 and 8.

(b) *Accident B:* Royal Navy Sea King, 26.9.1984

In another controlled ditching by a Sea King helicopter (accident 12 in Table 1 of Reference 3) a port engine failed whilst in a 30ft hover. The pilot lowered the collective to conserve rotor RPM and at about 4–5ft above the water, fully raised the collective to cushion the water impact. The aircraft entered the water in a slight nose down attitude with minimal forward speed. Water was reported to have broken over the windscreen on initial contact and the aircraft rolled right and then left before stabilising. A large volume of water entered the cabin through the cargo door on the initial roll to the right. No deformation of the underside of the fuselage was reported confirming that the impact with the water surface was well controlled. No injuries to occupants were reported. As with the previous accident, only the port flotation gear inflated successfully due to a problem with the firing button. The aircraft however remained afloat and upright for two hours.

5.2 Vertical Descent With Limited Control

(a) *Accident C:* Navy Lynx, 4.5.1983

Accident 14 in Table 1 of Reference 3 was briefly described in 3.2. A naval Lynx helicopter suffered a tail rotor failure at an altitude of approximately 400ft and with a forward speed of 120 Kts. An immediate engine-off descent was commenced and the aircraft entered the water in a nose down attitude with a low forward velocity and yawing to the left. Although the impact was cushioned by use of the collective, it was considered severe. The starboard flotation gear failed to operate due to damage to the electrical wiring during impact and the aircraft immediately rolled to starboard.

The fuselage structure suffered considerable damage on impact with the lower skins exhibiting significant water forming. The main vertical frames supporting the main rotor transmission above the cabin showed evidence of local buckling near the floor level and the cabin floor in this area suffered an upwards bending failure. The lower fuselage fore and aft beams in this area had undergone shear and bending failures. Damage to the main cabin section is shown in Figure 9. Crew seats were relatively undamaged but the floor attachments of the troop seats in the cabin were severely damaged. The tail cone failed in downward bending with evidence of it being forced to the left. No distortion or disruption was evident in the upper fuselage with engines, transmission and their fairings remaining intact and in place (see Figure 10). All four occupants suffered spinal injuries during the impact. Vertical decelerations at the crew stations were calculated to be in the range 18–22g.

Bending failures of the lower fuselage were attributed to the effect of water pressures generated by the severe vertical impact acting along the length of the fuselage. It has been calculated that forces required to initiate these bending failures will be generated by water pressure resulting from a 22 ft/s vertical impact onto water. The severity of this impact was intensified by the large flat area of the fuselage bottom in the aircraft in question; impact forces are proportional to area in vertical impacts as discussed in 4.1. It is considered that this impact would have been considerably less severe had the aircraft entered the water with a greater angle of pitch.

(b) *Accident D:* Royal Navy Sea King, 31.1.1972

Following problems with both engines, a Royal Navy Sea King helicopter (accident 58 in Table 1 of Reference 3) made a rapid descent onto water from a 42ft hover. The resulting impact was classed as severe (see Figure 11). The flotation gear inflated successfully and kept the aircraft afloat long enough for evacuation to be completed. The four cabin occupants were uninjured but one of the crew suffered a spinal injury. Examination of the two cockpit crew seats showed that the seat pans had been distorted downwards on impact. Buckling of the seat sides had also occurred on both seats. The lefthand crew seat had suffered more damage, due possibly to its occupant having been well forward in the seat at the time of impact. This factor, plus the lower level of restraint would explain why the occupant of this seat suffered injuries when the other crew member did not.

(c) *Accident E:* Royal Navy Sea King, 19.11.1974

In another Sea King accident (accident 49 in Table 1 of Reference 3), a tail rotor drive failure occurred whilst in a 40ft hover. The helicopter impacted the sea in a tail down attitude and rolled to port. The port fuselage suffered wrinkling of the hull and the sponson was badly damaged. Because of the roll attitude at impact, the starboard fuselage was relatively undamaged. Cockpit and cabin seats were undamaged and all occupants escaped without injury. The main cabin fuselage above floor level and the upper fuselage were also undamaged. Figure 12 shows the aircraft during salvage operations.

(d) *Accident F:* Civil S61, 17.10.1988

The accident to a Civil S61 helicopter, registration G-BDII (accident 19 in Table 6 of Reference 3) was the result of pilot disorientation during a search and rescue mission. It was calculated that the aircraft struck the sea in a 5° nose down attitude and banked 15° to the right. The aircraft was estimated to be moving forward at no more than 5 Kts and descending at 17 ft/s. On impact the fuselage immediately rolled over to starboard and partially sank. During impact with the sea, the starboard side of the boat hull was badly creased and there were ruptures in the skin in the areas of the lower forward fuselage, starboard cargo door and starboard rear door. The starboard sponson has been torn away. The tail boom, to the rear of its attachment to the fuselage was severely disrupted by impact forces. Although this was essentially an out of control accident, the impact conditions were considered to be similar to that for a vertical descent with limited control. The above information has been extracted from the Department Of Transport Air Accidents Investigation Branch Aircraft Accident Report 3/89 (Reference 36).

(e) *Accident G:* Civil Bell 212, 12.8.1981

A Bell 212, G-BIJF, lost control following a severe reduction in visibility (accident 66 in Table 6 of Reference 3). The aircraft hit the sea in a substantially level attitude with no forward speed but at a significant rate of descent. The lower fuselage suffered extensive deformation and tearing of skin panels. Fuselage frames and underfloor keel beams were also significantly damaged. The extent of damage to this aircraft is shown in Figures 13A, 13B and 13C. This information has been extracted from the Department Of Transport Air Accidents Investigation Branch Aircraft Accident Report 10/82 (Reference 18).

(f) *Accident H:* Civil Bell 412, 7.12.1987

The accident occurred as a result of a tail rotor gearbox separation at an altitude of 500ft (accident 27 in Table 6 of Reference 3). The pilot immediately lowered collective to enter autorotation and to arrest the spin to starboard; the spin, however, continued down to the water. Damage to the fuselage indicated that the aircraft impacted the water in a level attitude with a high vertical velocity. On impact the cabin roof collapsed downward and the lower fuselage was deformed upward between 8 to 12 inches. The main transmission was displaced to the left and evidence indicated that the main rotor blades had impacted the water and one had impacted the tail boom.

Examination of the cockpit revealed that the overhead structure had disintegrated and the windshield had shattered. Both energy absorbing crew seats remained attached to the seat tracks. The seats had stroked fully and both seat pans were deformed downward at the leading edges. Both crew members suffered spinal and facial injuries. This accident is reported in detail in Reference 37.

5.3 High Forward Speed Fly-in Accidents

(a) *Accident I:* Royal Navy Sea King, 13.10.1988

This accident has been reported briefly in 4.2 (accident 4 in Table 1 of Reference 3). Whilst both pilots were involved in diagnosing the cause of a vibration, the aircraft commenced a shallow descent and impacted the sea in a level attitude at a high forward speed. On impact, the aircraft remained upright on the surface and continued its forward travel but decelerating as it broke up. The aircraft broke up into three sections comprising the main cabin area forward of station 340 (see Figure 14), a central section between stations 340 and 520, and the tail cone. The locations of these sections are shown in Figure 15.

Most of the lower cabin structure forward of station 340 and the cockpit area were severely damaged to the extent that structural elements and equipment in these areas were retained only by electrical wiring. The upper fuselage including cabin roof, engine and main rotor transmission panels and fairings were relatively undamaged and displayed little water forming damage. The skin panels on the port side of the tail section displayed buckling due to compression along most of its length.

Both cockpit seats were rotated outboard about their outer seat rails as the cockpit floor was severely disrupted . An upward bending of the cockpit floor is believed to be due to water pressures resulting from an inrush of water into the area beneath this floor. Failure or removal of the electronics compartment door mounted in the nose of the aircraft (see Figure 8) would allow water entry into this area. After the sections of the fuselage had submerged, one cockpit crew member surfaced still strapped in his seat and suffered only minor bruising.

It was noted in the aircraft accident report from which the above information has been taken that the deceleration of the aircraft through the water undoubtedly attenuated the impact forces applied to the crew. A steeper descent angle or greater nose down attitude would not have allowed the aircraft to continue forward motion through the water and would have undoubtedly resulted in a more severe crash environment.

(b) *Accident J:* Royal Navy Lynx, 10.3.1988

This accident was caused by the aircraft flying into the sea at high speed in a shallow angle descent and was probably the result of pilot error or disorientation (accident 7 in Table 1 of Reference 3). The aircraft was estimated to have impacted the sea with a forward speed of 55 Kts in a 3° nose down attitude. As the Lynx has a fixed tricycle undercarriage, the attitude of the aircraft at impact may have been the result of a nose down pitch moment induced by immersion of the undercarriage. The aircraft floated inverted after the impact in a 30° nose down attitude supported by its own flotation bags.

On impact with the water surface, the forward fuselage sustained severe damage. The nose structure forward of the windscreen remained attached to the main fuselage only by harnesses of electrical cables. Behind this, the cockpit forward bulkhead, on which is mounted the instrument panel, showed evidence of heavy water forming and had become detached along its lower edge. Figure 16 shows how this area of the structure, including the instrument panel, had been twisted and pushed rearwards into the cockpit. Both seats remained attached to the airframe although both seat backs had been bent rearwards.

Little damage was evident in the upper fuselage, with engines, main rotor transmission and their fairings remaining in place and relatively undamaged. Little water forming of the lower fuselage was discernable (see Figure 17) indicating that the vertical velocity at impact was low.

(c) *Accident K:* Civil S61N, 16.7.1983

Whilst in a straight and level flight, a civil S61N helicopter, G-BEON, gradually descended from its intended altitude of 250ft and flew into the sea (38) (accident 51 in Table 6 of Reference 3). The aircraft struck the water in a slightly nose down attitude, banked slightly to port and at a forward speed of 80–100 Kts. As the aircraft was less than 2 nautical miles from the airfield, the helicopter's landing gear was down at the time of impact. After three successive impacts with the sea, which was calm, the helicopter rolled over and sank almost immediately. During the impact both sponsons were broken off together with the flotation gear. The force of the impact destroyed the aircraft hull below floor level for most of its length and allowed an inrush of water to burst open the two freight bay hatches in the forward and rear cabin floor. Figures 18 and 19 show the extent of structural damage to G-BEON.

The aircraft was equipped with seats for twenty four passengers and one fold up seat for the cabin attendant. Passenger seats along the port wall of the fuselage were all single seats, those along the starboard wall were double seats. The cabin attendants seat had failed in a forward direction and had pulled completely away from the aircraft floor structure. Tests carried out on a deceleration track at the Royal Airforce Institute Of Aviation Medicine resulted in a similar failure at a longitudinal deceleration of 6g. Six of the seven double seats had separated from the fuselage as a result of the impact. The results of deceleration tests on these double seats indicated that they could withstand deceleration of about 12g before failure.

The bodies of seventeen passengers were found in the fuselage. A post-mortem examination revealed that all had died from drowning and that none had sustained any incapacitating injury. Only three of the seventeen bodies showed evidence of lap strap bruising or abrasion. In a review of human tolerance to impact accelerations, Glaister (39) has shown that for occupants wearing a lap belt only, tolerance to injury is considerably lower than for a system incorporating an upper torso restraint. This is due to the very high local belt loads and risk of injury to abdominal organs as the body jackknives over the lap belt. An average deceleration of 15g is quoted as a tolerable level for longitudinal impacts.

In the Boeing 737 Kegworth accident in 1989, maximum longitudinal decelerations in the areas of the fuselage away from the point of impact were calculated to be in the range 20–25g (40). Thirty four percent of the survivors suffered abdominal injuries and demonstrated significant abdominal bruising associated with the wearing of the lap type safety belts. For the eighty seven survivors, there were one hundred and forty two occurrences of pelvic and lower limb injuries and fifty nine cases of upper limb injuries attributed to body flailing under fore-aft decelerative forces.

On the above evidence, it is considered that the accident to G-BEON was not as severe as that of the Kegworth Boeing 737 accident in terms of the fore-aft crash forces and that peak decelerations were survivable and probably below 20g. Had water entry into the lower fuselage and cabin been prevented, then lower fore-aft decelerations would have been generated due to the reduced drag. Had the seat been designed to a higher static strength or dynamic criteria and fitted with upper torso restraints, it is considered that occupants would have been better able to evacuate the helicopter.

(d) *Accident L:* Civil Bell 212, 14.9.1982

A Bell 212, G-BDIL, was flying at a low altitude to maintain visual reference with the surface of the sea (41) (accident 56 in Table 6 of Reference 3). Impact with the water probably followed a banked turn to the right with a resultant loss of height. From the probable flight path, aircraft speed at impact was estimated to be in the region of 100 Kts. The fuselage suffered severe impact damage particularly to the forward right quarter that was consistent with a high speed impact when flying nose down and banked to the right. The right skid had been torn off whereas the left skid remained in position. Instrument panel and centre console were recovered attached to the fuselage by electrical wiring. The main rotor assembly had become detached during the impact. The rear end of the tail had suffered a main rotor blade strike and the tail fin and tail rotor assembly had separated. The level of structural damage to G-BDIL is shown in Figures 20 and 21.

(e) *Accident M:* Lynx, 4.1.1984

Structural damage following a more severe fly-in accident than that reported under Accident J is shown in Figure 22. In this accident, a naval Lynx helicopter struck the sea at a shallow angle at an estimated 100 kts forward speed. Substantial damage to the lower fuselage indicated that the forward fuselage and cockpit area separated following a catastrophic failure in this area. The structure forward of this failure was not recovered. Damage to the lower surface of the fuselage is shown in Figure 23.

A KRASH analysis of this impact, reported in Reference 5, predicted that the nose structure would have failed in downward bending followed by a complete forward turnover of the aircraft. The extensive damage to the upper fuselage, as shown in Figure 22, suggests that the aircraft contacted the water at high speed in an inverted attitude and confirmed the KRASH prediction. The severity of this impact was undoubtedly due to the nose of the aircraft submerging below the water surface and the forward fuselage failing under the applied water pressure. The Lynx KRASH model and predicted aircraft response to a high forward speed shallow angle fly-in water impact are shown in Figures 24 and 25.

Damage to the lower fuselage of an Army Lynx helicopter involved in a near identical 100 kts forward speed shallow impact with water is shown in Figure 26. Unlike the previous naval Lynx accident, however, the forward fuselage did not fail but showed extensive water forming and evidence that the nose had not immersed further than about 9 inches below the water surface. The ability of this structure to remain above the water surface by generating sufficient hydrodynamic lift during forward motion through the water resulted in a significantly less severe impact.

The difference in behaviour between the Army and Navy Lynx structures in high forward speed fly-in accidents is attributed to the design of the forward fuselage. The nose of the Army Lynx, shown in Figure 27, is a continuous structure fabricated from aluminium alloy broken only by access panels in the side. Underfloor fore and aft keel beams extend almost to the nose of the fuselage. The Navy Lynx structure, however, terminates at a large vertical bulkhead just forward of the windscreen. The area forward of this station contains a radar housed in a composite honeycomb sandwich panel fairing. It is considered that this fairing would offer little resistance to the applied water pressure and would fail on contact with the water surface. Exposure of the internal vertical bulkhead to the inrush of water would generate forces of a sufficient magnitude to cause a catastrophic failure at forward speeds of 100 kts.

A different mode of structural failure was evident for the Army Lynx helicopter. As described above, hydrodynamic lift forces prevented the nose of the aircraft from submerging. The aircraft remained above the surface of the water and continued forward motion under a gradual deceleration. The upward forces in the lower fuselage generated by hydrodynamic lift, however, were opposed by the inertia forces associated with the large mass items in the upper fuselage that generated a nose down pitching moment. A consequence of these opposing forces was a bending failure of the lower fuselage at the same station as the failure shown in Figure 9.

5.4 Accident To G-BEWL: 25.7.1990

This accident, although classed as out of control and therefore not within the three impact categories discussed above, has been included on the grounds of the level of detail recorded during the accident investigation and the nature of the accident. This accident is identified as accident 11 in Table 6 of Reference 3 and reported in Department of Transport Air Accidents Investigations Branch Aircraft Accident Report 2/91 (33). After striking part of a crane structure on the oil platform Brent Spar, the civil S61N G-BEWL sank rapidly onto the helideck. Before occupants could escape, the helicopter fell from the edge of the deck into the water 105ft below and sank in less than one minute.

The pattern of damage to the skin of the lower fuselage and the right hand sponson indicates that at impact with the water, the helicopter was at an attitude 10° nose down and at a roll angle of 10° to starboard. Hence the major impact was vertical with minor longitudinal and lateral components. The impact was considered to be less severe in the rear of the cabin than in the forward fuselage. The impact velocity was calculated to be between 70 and 80 Kts giving a peak vertical deceleration in the range 20–25g at the cabin floor.

Three main airframe failures occurred on initial contact with the water surface. First, the right hand sponson became detached. Secondly, the fuselage suffered a bending failure between the rear cockpit bulkhead and the main cargo door. The cockpit structure forward of this break was severely disrupted. Thirdly the tail boom had failed and folded to the left. Both cockpit seats had remained in place in the cockpit and had not suffered any significant collapse. However, both seats had sustained forward bending of the upper seat back due to intrusion into the cockpit of the structural bulkhead immediately behind these seats during structural collapse of this part of the fuselage.

All occupied passenger seats showed some degree of damage from minor deformation to complete collapse. In all cases deformation was limited to within the structure of the seat; seat to airframe attachments remained undamaged. Injuries to many passengers were consistent with seat failures that allowed occupants to move forward and to the right. Flailing of the upper torso around the lap belt that resulted in head contact with the seat in front or adjacent structure, was identified as a primary injury mechanism.

6 ANALYSIS OF STRUCTURAL RESPONSE TO WATER IMPACT

This programme was not intended to be a definitive quantitative investigation into structural response but simply to consider the effect of shape and stiffness of generic helicopter structures under vertical water impacts. As such, a simplistic modelling approach was adopted. To reduce modelling complexity and computer costs, structures were modelled as 2-dimensional representations. Only two parameters were monitored, vertical deceleration and vertical displacement of the fuselage floor. Although it is recognised that changes in the shape of a structure may also affect structural response, this was not monitored. It was also recognised that more efficient finite element techniques are now available for modelling water impact, e.g. MSC/DYTRAN. At the time of this study, however, DYNA3D and MSC/DYNA were the only computer programs available.

6.1 Overview of DYNA3D

DYNA3D is a 3-dimensional finite element program for analysing the dynamic behaviour of structures. It uses explicit time integration of the equations of motion and incorporates features to simulate a wide range of material behaviour. The code uses the finite element approach whereby a structure and for example an impact surface, are represented by a mesh of elements. Each element is assigned dimensions and representative mechanical and physical properties.

The element formulations available include one dimensional beam elements, two dimensional shell elements and three dimensional solid or brick elements. The program contains a sophisticated contact interface capability to model interaction between independent bodies and between different areas of one body. DYNA3D was developed by Dr J O Hallquist in 1976 at Lawrence Livermore National laboratories and has been updated and improved through a number of later versions. It is now recognised as the industry standard for the dynamic analysis of structural behaviour. A detailed review of DYNA3D can be found in reference 42.

6.2 **Study by Frazer-Nash Consultancy Limited**

An analysis of the vertical impact of various generic helicopter shaped structures with water using DYNA3D was carried out by Frazer-Nash Consultancy under this current CAA contract in 1993. Three fuselage shapes were analysed, a cylindrical structure, a flat bottomed structure and a V-bottomed or boat hulled configuration. These structures are shown in Figure 28. The effect of fuselage deformation was also analysed by considering three different configurations for each shape. In one case the structure was modelled as a rigid body. A second case assumed the structure to be an elastic-plastic shell. The third configuration was again elastic-plastic but included additional stiffness from an internal fore-aft keel beam along the model centre-line. All three configurations were modelled with a fuselage shell thickness of 10 mm.

The fuselage shell was modelled using plate elements to which were assigned material properties representative of a conventional aluminium alloy. Because one objective of this investigation was to look at deformation of the lower fuselage, the floor of the fuselage was considered to be rigid. The water was represented using DYNA3D's hydrodynamic material. For this material the user can specify a material density and an equation of state which describes the pressure/volume characteristics of the material. To reduce computer costs, one half of the fuselage was modelled with appropriate constraints being applied on the plane of symmetry. The structure was modelled as a one element thick 'slice', thereby producing a 2-dimensional representation, again to reduce modelling complexity and costs. Impact with water was modelled at a vertical velocity of 7 m/s. This velocity is similar to the wheels up vertical landing case specified in MIL-STD-1290 for US Military Helicopters (32). A detailed description of the model geometry and properties is given in Reference 43.

A summary of peak vertical decelerations of the structure and the vertical displacement of the floor (this displacement is an indication of the extent of model immersion below the water surface and structural deformation) are shown in Figure 28. Of the three rigid body models, the cylindrical fuselage (case 1) demonstrated the lowest deceleration of 10·6g. As expected the V-bottomed fuselage (case 7) generated lower decelerations than the flat bottomed configuration (14·9g compared to 17·9g). For the elastic-plastic structures, the lowest deceleration was again generated by the cylindrical shape with 4·9g and 7·6g for the two configurations. For the other fuselage shapes, however, the flat bottomed structure generated lower decelerations than the V-bottomed shape. For the structure with the central fore-aft keel beam stiffener, for example, decelerations of 8·8g and 11·7g were calculated for the flat bottomed structure (case 6) and the V-bottomed shape (case 9) respectively.

The vertical displacement of the floor at peak decelerations for both rigid body and elastic-plastic structures are shown in Figure 28 to demonstrate little or no correlation with the magnitude of deceleration. Although floor displacements, comprising fuselage deformation and water immersion, undoubtedly produce a reduction in deceleration, as indicated by the lower decelerations for the elastic-plastic structures, large displacements do not necessarily result in lower decelerations. Case 8 in Figure 28, for example, demonstrates the third highest deceleration and the largest vertical floor displacement. By comparison, in impacts onto a rigid surface deceleration levels are directly related to the distance over which the deceleration takes place.

In explanation it is considered that the shape of the deformed structure, in addition to the extent of deformation, will play an important role in determining deceleration levels. The shape of the fuselage will control the virtual mass of water associated with the fuselage as described in 4.1 and hence influence structural response.

6.3 Further Water Impact Analyses at WHL

The work initiated by Frazer-Nash Consultancy and discussed above has been extended by analysing further cases at WHL. The same geometries as those modelled by Frazer-Nash were analysed using MSC/DYNA. This finite element program is an enhanced commercial version of the public domain DYNA3D program with support and documentation provided by MacNeal – Schwendler Corporation. More attention has been directed in this study to the extent and mechanism of deformation in the generic helicopter structures by varying structural stiffnesses. Analyses were again limited to a 7 m/s vertical impact onto water. Because of computer post processing limitations, a coarser finite element model and a coarser frequency of time-history output than that used by Frazer-Nash Consultancy were adopted for this study. A summary of the response of structures analysed using MSC/DYNA is shown in Figure 29.

A cylindrical fuselage with a reduced stiffness to that analysed by Frazer-Nash (i.e. a 7·5 mm shell thickness) and without a fore-aft keel beam generated the lowest deceleration of the cases analysed. The peak deceleration of 4·1g for case 10 is shown in Figure 30 together with the fuselage displaced shape at the time of peak deceleration. In this case the 0·5 m vertical displacement of the floor consisted solely of structural deformation of the lower fuselage; there is no significant immersion of the fuselage below the water surface. The second lowest deceleration, generated by case 11, showed a significantly different pattern of deformation. This structure was identical to case 10 above but the central fore-aft keel beam had been included. A peak deceleration of 5·3g and displaced shape at 0·05s after impact is shown in Figure 31. Unlike the previous case, vertical displacement of the floor is made up of components of both structural deformation (0·15 m) and immersion below the water surface (0·15 m).

An example of one of the highest decelerations recorded for the cylindrical structure is shown in Figure 32 (case 12). Although the level of structural deformation and water immersion were very similar to case 11, the peak deceleration was significantly higher at 8·1 g. The higher deceleration recorded for this structure compared with case 11 was believed to be due to the different deformed shape generated on impact with the water surface.

A comparison of water and rigid ground impact for the same structure showed similar peak decelerations, 8·1g for a water impact case (case 12) and 7·9g for a rigid surface impact (case 13). However, these structures exhibited very different deformation patterns. Little deformation occurred for the water impact; 0·15 m structural deformation plus 0·15 m water surface immersion producing a total vertical displacement of the floor 0·3 m at the time of maximum deceleration. For the impact onto a rigid surface, (see figure 33), structural deformation resulted in 0·58 m vertical displacement of the floor.

It was noted that for impacts with a rigid surface, the peak deceleration occurred at the same time, 0·13s, as the maximum structural distortion (see figure 33). For the water impact, however, the peak deceleration occurred much earlier in the impact sequence, i.e. 0·05s and that structural deformation continued for a significant period beyond this time.

For the flat bottomed fuselage shape shown in figure 29 the deceleration levels for a 7 m/s vertical impact onto water were greater than the cylindrical fuselage for all configurations and stiffnesses investigated. This fuselage shape is perhaps more representative of most of the helicopters currently in-service. Case 14 was similar to the configuration used by Frazer-Nash Consultancy and was considered as a reference structure. The peak deceleration recorded for this study using MSC/DYNA was 9·1g (see figure 34); Frazer-Nash Consultancy recorded a peak deceleration of 8·8g (case 6) using DYNA3D. This difference of 3% between solutions is considered acceptable given the differences in the material models between the two programs.

The highest deceleration recorded was for Case 15, 12·3g (see figure 35). In this configuration, the fuselage outer skin was double the thickness (i.e. 20 mm) of that used in the Frazer-Nash study. Figure 36 shows the vertical displacement time history for grid points on the top surface of the fuselage floor and the lower bottom surface. Although this model showed a vertical displacement of the floor of 0·12 m at 0·02s, the lower fuselage can be seen to rebound away from the water surface at the time of peak deceleration.

The lowest deceleration of 8·1g was shown in case 16 (see figure 37). This configuration consisted of a 7·5 mm thick outer shell and a central stiffener or keel beam twice the stiffness of that used in the Frazer-Nash study. Although showing similar vertical displacements of the floor to other cases (i.e. 0·13m at peak deceleration) this model demonstrated the greatest level of immersion below the water surface. Figure 38 shows the vertical displacement – time histories for the upper and lower surfaces of the model for case 16 and case 14 (the second lowest deceleration). Comparisons between the structural deformations in these cases, shown in figures 34 and 37 show a significant difference in the mode of structural deformation.

Case 17 was of a similar structural configuration to case 16 but with the addition of a second vertical stiffener or bulkhead mid way between fuselage centreline and outside edge (see figure 33). This structure demonstrated a similar vertical displacement of the floor as case 16, i.e. 0·13 m (compare figures 38 and 40); the additional stiffener, however, reduced the level of structural deformation. This configuration demonstrated the second highest deceleration, 11·1g, of the structures analysed. A summary of peak decelerations for the structures analysed at WHL is shown in figure 33.

7 DESIGN TECHNIQUES FOR IMPROVED RESPONSE OF HELICOPTER STRUCTURES TO WATER IMPACT

The primary objectives of designing for crashworthiness and occupant safety are to maintain a protective shell for occupants throughout the impact sequence, to prevent hazardous displacement of large mass items and to limit decelerations transmitted to the occupants to within human tolerance levels. The design techniques and procedures to achieve these objectives for land impacts are well documented in the Aircraft Crash Survival Design Guide (1). From the work carried out in this and other studies, however, it is clear that designing for water impact survival requires a different approach.

When designing for water impact and ditching, the fundamental issue that must be addressed is whether the fuselage can be designed to withstand the hydrodynamic forces generated on contact with water without excessive weight penalties. It has been shown previously that it is the break up of the airframe on contact with water (an event far more likely than for land impacts) and the associated inrush of water that produces the major hazard to occupant survival (8). Injuries directly attributable to failure or collapse of the airframe have been shown to be only of secondary importance in helicopter water impacts (3). If the fuselage cannot be designed to withstand water impact loads, consideration should be given to whether ditching aids, e.g. water skis, could be employed to reduce the severity of the impact and improve the probability of occupant survival.

7.1 Longitudinal Water Impacts

It is considered that most aircraft could be ditched with relative safety if extensive damage to the fuselage could be avoided; the strength of the lower fuselage is the most important parameter influencing the ditching behaviour of fixed wing aircraft (35). For example, many fixed wing aircraft can be ditched successfully at over 130 kts if a favourable nose up attitude can be maintained (34). For this case it has been shown that a fuselage strength of 12–17 lb/in^2 is adequate to prevent excessive damage (34). Aircraft decelerations in the longitudinal and vertical directions are typically 3·5g and 6g respectively and are within the structural capability of the airframe. If the attitude of the aircraft at impact is less than favourable, e.g. excessive pitch angle, significant damage to the lower fuselage will result in considerably higher decelerations; vertical decelerations as high as 17g have been recorded (34) and are likely to result in break up of the aircraft. Fuselage strengths of the order of 35 lb/in^2 have been shown to be required to permit successful ditching in less than ideal conditions (34).

Fuselage strengths of many fixed wing aircraft, particularly large transport aircraft, are high because of cargo requirements and the need for pressurised cabins. The average resistance to water loads is estimated by manufacturers to be 8–17 lb/in^2 (34,35). In helicopter design, however, the lower fuselage is generally designed to much lower strengths, typically 5–9 lb/in^2 and the ditching performance is subsequently reduced. With the lower fuselage designed to this strength, ditching at forward speeds of 25–35 kts will be possible if it is assumed that sufficient control exists to maintain an optimum nose up attitude in the water. While the hydrodynamic peak pressures on initial contact will be relatively large (pressure is proportional to the square of the velocity and the angle of the structure relative to the water surface), they will act over a very small area if the aircraft enters the water in a nose up attitude. The reduction in forward velocity as the aircraft decelerates will reduce peak pressures as the hull penetrates further into the water. Although a small area of the lower fuselage may experience 9 lb/in^2, for example, the majority of the lower surface would see peak pressures in the region 3–5 lb/in^2. Aircraft decelerations at these speeds will generally be less than 3g and well within the capability of the airframe for current aircraft.

At forward speeds below 35 kts and with sufficient control to ensure a favourable nose-up pitch attitude, controlled ditchings and a proportion of limited control water landings should be able to be successfully undertaken for current standards of helicopter design. That is the strength of the fuselage should prevent structural failure and limit the extent of water entry into the fuselage. The failure of low strength access panels, glazing panels and doors, however, may still allow water to enter occupied areas. Even in the more severe limited control accidents where serious injuries are involved, the structural strengths of current helicopter design (particularly military helicopters) are generally sufficient to maintain structural integrity. Damage is likely to be limited to rear fuselage and tail cone failure and severe water forming of the lower fuselage.

Longitudinal impacts into water at speeds above 40 kts are likely to generate water pressures of a sufficient magnitude to severely damage or fail lower fuselage panels regardless of the attitude of the aircraft or degree of control. For example, from unpublished data held by WHL, it has been shown that pressures in excess of 30 lb/in^2 have been generated in a 40 kt longitudinal impact. For fly-in accidents, the aircraft is invariably in a level or slight nose down pitch attitude. In this class of accident extensive damage to the fuselage is likely because of the greater area of the fuselage in contact with the water surface.

To prevent major structural failures and to reduce the severity of water impacts in future helicopter designs, two design approaches may be considered. The outer fuselage skin may be designed to withstand the water pressures generated on impact without inducing excessive aircraft decelerations and without allowing water to enter internal structural compartments. Alternatively the internal structure that is likely to come into contact with the water surface must be designed to offer the least drag resistance to allow forward motion of the aircraft to continue in a controlled manner and without excessive deceleration. The inrush of water into occupied areas must also be prevented.

Design approaches may include a double skin to the bottom of the fuselage, i.e. a conventional strength aerodynamic outer skin and a high strength inner skin. In this case the inner skin should be configured to carry flight and landing loads rather than being a parasitic structure. Alternatively, for a conventional structure comprising keel beams and transverse bulkheads in the underfloor structure, vertical surfaces should be avoided by canting bulkheads rearwards. Design approaches for the forward fuselage to withstand water impacts are shown in Figure 41.

Longitudinal decelerations even in severe longitudinal water impacts have been shown to be relatively low based on the low incidence of crash force related injuries. The accident review in reference 3 identified very few instances of longitudinal water impacts in which the strength of the airframe main load paths had been exceeded or large mass items such as engines and transmissions had not remained attached to the airframe. Hence, the problem of designing to survive water impacts is not one of absorbing energy to reduce crash forces but of designing to withstand water pressures. Structural damage resulting from excessive water pressure and the inrush of water into occupied areas were found to be major factors contributing to occupant injuries.

A further significant factor contributing to injuries in civil helicopter accidents was found to be the low strength of passenger seats. An example is the accident to the civil S61N G-BEON on 16th July 1983. In this accident the aircraft flew into the sea in an essentially level attitude at approximately 100 kts. The impact was survivable in that the deceleration levels were within the structural capability of the airframe allowing the cabin and upper fuselage to remain intact.

Failure of the passenger seats under longitudinal deceleration, however, resulted in incapacitation of the occupants and loss of life through drowning when the aircraft sank. Water impact damage to the lower fuselage allowed an inrush of water into the cabin and contributed further to occupant incapacitation. The frequency of survivable high forward speed water impacts has been noted by Glancy (6). In an analysis of US Navy helicopter accidents it was shown that significantly higher longitudinal velocity water impacts were survivable compared to land impacts. From Figure 42, it can be seen that the 95th percentile potentially survivable impact velocity is in excess of 120 ft/s compared to 80 ft/s for US Navy land impacts and 60 ft/s for US Army land impacts.

In addition to the problems associated with failure of outer skin panels, other features of helicopter design may also reduce the ability to withstand longitudinal water impacts. Wheel wells and undercarriage retraction bays, for example, are often constructed from vertical bulkheads that can generate high drag forces on contact with water. It has been shown that a tricycle undercarriage arrangement in a fixed wing aircraft is less effective in water impacts than a tail wheel design as water entry into the nose wheel bay may cause a nose down pitching moment. Furthermore, an in rush of water into such a bay may cause further damage to internal structure (35). Access panels are likely to have considerably less strength than the surrounding structure and may be further sources of water entry. The vulnerable electronics bay door in the nose of the Sea King helicopter is an example. Water entry through this bay has been known to disrupt the cockpit floor and result in failure of the crew seat to floor attachments. To improve the ability of helicopters to withstand longitudinal water impacts, openings in the lower fuselage should be avoided wherever possible. If they are unavoidable, the internal structure of such bays should be designed to offer the least resistance to motion of the aircraft through the water. In addition, the possibility of water passing from these bays into occupied areas (e.g. through failure of cockpit and cabin floor structure) should be prevented. Wherever possible, the panels covering openings and bays in those areas of the fuselage likely to contact the water should be of an equal strength to the surrounding structure.

One factor that determines the severity of longitudinal water impacts is whether the aircraft remains on the surface throughout the impact sequence. Aircraft that are able to continue forward movement along the surface of the water and decelerate in a controlled manner sustain significantly less structural damage and few injuries. Aircraft that pitch nose down into the water, however, invariably suffer extensive damage to the forward fuselage. Catastrophic structural failures, forward turnover of the aircraft and a greater probability of injury are associated with this type of impact. Whether the aircraft remains on the surface or pitches nose down is not a function of velocity but is dependent on the shape and configuration of the fuselage. Structural features and protuberances below the lower surface of the fuselage that may induce or exacerbate nose down pitching should be avoided where possible. In cases where potentially detrimental features are unavoidable, e.g. fixed undercarriages, undercarriage sponsons, external fuel tanks, they should be designed to minimise nose down pitching of the aircraft. The possibility of designing these features to generate a nose up pitching moment should be investigated.

One method of preventing excessive nose down pitching of an aircraft during longitudinal water impacts is to provide a device under the nose or forward fuselage forward of the centre of gravity that will generate sufficient hydrodynamic lift to produce a positive or nose up pitching moment. These 'hydroflaps' have been successfully tested on scale models of fixed wing aircraft (35). Another possible ditching aid is a planing surface that can be extended on struts or undercarriage legs so that on contact with water the aircraft rides on the planing surface and the fuselage is not subjected to high water pressures. Such a device has been successfully applied to aircraft that for aerodynamic purposes, e.g. supersonic aircraft, are not of an ideal shape to survive water impacts. Generating hydrodynamic lift on the forward fuselage to prevent immersion can create significant bending moments in the fuselage if an opposite nose down pitching moment is enforced at the rear of the fuselage. Designers, therefore, should be aware of modes of structural loading that may not have been considered in the normal design process.

7.2 Vertical Water Impacts

The response of structures to vertical impacts onto water has been shown in 4.1 to involve a fundamentally different mechanism of loading to ground impacts. Loads are distributed over a large area of the lower fuselage with the result that skin panels become highly loaded. Under severe hydrodynamic loads these panels can fail between the beams and bulkheads; any potential energy absorption capability built into these elements will, therefore, not be utilized. As a result vertical impacts onto water may be expected to be more severe than land impacts.

To reduce the severity of vertical impacts, controlled structural collapse of the under floor structure must be encouraged by increasing the strength and stiffness of the belly panels to prevent rupture and to distribute loads to the main structural elements. Configuring the structure such that the outer skins are load bearing, as in a monocoque construction, rather than being designed to aerodynamic loads would ensure a more efficient distribution of loads. Alternatively, a multi-element construction involving a large number of individual beams and stiffeners and relatively small areas of unsupported skin, such as the design shown in figure 26 would also ensure an efficient distribution of loads.

The shape of the lower fuselage has been shown in section 6 to have a significant effect on deceleration levels during a vertical impact onto water. For a rigid structure, a shape that can penetrate the water with least resistance will generally result in the lower deceleration; the less the volume of water displaced, the lower the deceleration. However, it was also shown that structures of an ideal configuration for penetrating the water in an undeformed state, may generate higher decelerations when deformed by the impact. Although deformation in the lower fuselage reduced the vertical decelerations for all the structures analysed, the magnitude of the resulting deceleration depended strongly on the mode of deformation. For a flat-bottomed lower fuselage, for example, decelerations varied from 8·1g to 12·3g for different modes of deformation. As a general guideline it was found that designs with a high stiffness central keel beam to maintain or promote a 'V' shape to the lower fuselage, generated the lower decelerations. As any water landing apart from a fully controlled ditching will result in damage to the lower fuselage to some degree, consideration should be given to the likely mechanism and pattern of deformation during design.

As reported by Johnson (20), uncontrolled or unplanned water impacts invariably result in greater fuselage damage than corresponding ground impacts. In section 5 of this paper examples have been quoted of aircraft sustaining substantial damage and catastrophic failures in accidents where the forces generated are within the design capability of the aircraft. Although the main structural load paths in these aircraft may have been designed to withstand high inertia loads in vertical and longitudinal crash cases, it is often the lack of fuselage strength in bending, particularly the lower fuselage, that results in airframe failure in vertical or near vertical impacts. The application of differential water pressures along the length of the airframe or the presence of a pitch attitude on entry into water can generate significant bending moments in the fuselage. The tendency in many current helicopter designs to cantilever the cockpit structure off the main cabin fuselage does little to improve the bending strength of the lower fuselage and may increase the probability of structural failure. To reduce the probability of bending failures, the fuselage should be of a 'box' construction with the floor, roof and vertical frames or bulkheads all forming elements of the main structural load path.

As in the case of designing for longitudinal water impacts, access panels in the lower fuselage should be avoided or be designed to withstand the applied water pressures. Because of the lower velocities and the shorter distance moved by the fuselage through the water in vertical impacts, the need to maintain a low drag profile is not as great as for longitudinal impacts. However, it is still important for the panels to remain in place to prevent an inrush of water into the lower fuselage and occupied areas.

8 DISCUSSION

This study has investigated the impact behaviour of helicopter structures in accidents involving collision with water. It has been shown that the response of structures to water impact is significantly different from that of ground impacts. In an earlier study (3), for example, it was shown that the cause of death in the majority of both civil and military helicopter water impacts, where a cause had been identified, was drowning. Fatalities resulting from impact forces that produce decelerations in excess of human tolerance or lead to collapse of the airframe structure, were a secondary and minor cause of loss of life. By comparison, impact forces have been shown to be the primary cause of fatalities in land impacts (11). In a study by Glancy (6) of the impact conditions of US Naval helicopters, it was shown that for both vertical and horizontal impacts with water, higher impact velocities were survivable than for US Navy and US Army ground impacts (see figure 42). The term survivable here means impact survivable, however, and does not consider post crash survival issues.

The high incidence of helicopters inverting or sinking, even in relatively minor water impacts and controlled ditchings, account for the high fatality rates in water impacts (3). The major cause of drowning is the inability of the occupant to escape from a submerged helicopter. Disorientation due to the inrush of water through doors, windows and structural failures, inability to locate or open exits and incapacitation due to injuries are the main reasons for the inability to escape. The poor flotation characteristics of current helicopter designs, and in particular the vulnerability of flotation systems to relatively minor structural damage, has been reported in several studies (for example 8, 10). In the aircraft accident report for G-BIJF (18), a Bell 212 that collided with the water in a vertical impact, two recommendations were made relating to the inadequacy of the current BCARs covering the downward rate of descent (1·5 m/s) required for flotation equipment. Localised structural damage was found to have resulted in failure of flotation system pipework and electrical wiring in this and other water impacts (see for example 44).

From an earlier review of UK military and world civil helicopter impacts (3), it was shown that over 70% of accidents could be categorised into three impact types: controlled ditching, descent with limited control and fly-in accidents. Controlled ditchings accounted for 32% of military and civil accidents; there were no recorded serious injuries but four fatalities due to drowning in this class of accident. Structural damage was restricted to minor water forming of the lower fuselage and tailcone or rear fuselage failures. Twenty six percent of the accidents were limited control descents. In the military helicopter accidents, all eight injuries were spinal injuries in predominantly vertical impacts. Of the eight documented injuries to civil occupants (out of a total of 47), six were again spinal injuries due to vertical forces. Forces generated on impact were generally within the capability of the airframe in this class of accident although minor structural failures were sometimes evident. Failure of access panels and lower fuselage panels were frequently observed in the more serious impacts. These failures allowed an inrush of water into occupied areas that contributed to occupant disorientation and egress difficulties. The high incidence of spinal injuries in these accidents indicates the severity of vertical impacts into water.

Fifteen percent of military and civil helicopter water impacts were found to be high forward speed fly-in accidents and were primarily due to pilot error or disorientation. This class of accident accounted for 73% of fatalities in military helicopter water impacts and 23% of fatalities in civil accidents. Over 60% of occupants in these accidents drowned. In these fly-in accidents, as in the previous two categories, the crash forces rarely exceeded the strength of the main load path structure. However, the generation of high water pressures in these high forward speed impacts frequently resulted in substantial airframe damage and in some cases catastrophic failure of the aircraft. Major structural failures and separation of the fuselage allowed a considerable inrush of water into the fuselage and a more rapid sinking. These accidents, regardless of the forces involved, have been shown to be far less survivable than accidents in which the airframe remains intact (20).

As relatively few fatalities were found to be attributable to excessive crash forces, it is considered that many of the crashworthiness design features developed for ground impacts are not applicable for designing for water impacts. The provision of additional energy absorbing structure to reduce deceleration levels and improved attachment strength of large mass items, for example would not have provided any significant improvement in occupant survival in the accidents reviewed in Reference 3. Accidents in which engines or transmission attachments failed or the main structural load paths collapsed due to excessive inertia crash forces were rare and generally limited to out of control and very severe fly-in accidents involving civil helicopters. In the accident to the Bell 212 G-BDIL for example (accident L in 5.3) the main rotor mast and gearbox assembly separated from the fuselage through a failure of the gearbox case.

For accidents in which crash forces have been estimated or calculated, peak decelerations have been below 20–25g. Transient decelerations of this magnitude are within the limits of human tolerance for restrained occupants and are also generally within the structural capability of the majority of military helicopters and civil derivatives of military designs currently in service. The vertical and longitudinal crash load factor for the structure supporting the engines and main transmission in the military Sea King helicopter, for example is 20g. Crew seats in military helicopters are generally designed to or have been dynamically tested to strengths in the range 15–20g. No evidence of failure to military helicopter seats was found although seat deformations were observed in a number of accidents. In several cases the detachments of crew seats were recorded due to failure of the cockpit floor under water pressure loads (see accident I in 5.3).

The failure of civil seats, and in particular, civil passenger seats, have been found to be a major cause of occupant injury. An example is the S61N, G-BEON, where a high forward speed impact resulted in failure of nearly all cabin seats under fore-aft loading (38). These failures resulted in severe occupant disorientation and secondary contact injuries to the extent that when the aircraft subsequently sank, 17 of the 23 passengers drowned inside the cabin.

The severity of an impact with water has been shown to be dependent on both impact velocity and the behaviour of the aircraft on entry into water and that it is the resultant water pressure rather than inertia forces that determine the response of the structure. In longitudinal impacts, it is the resistance to movement through the water that determines the loading in the aircraft. A low drag structure will generate lower fore-aft decelerations than one with a higher resistance. The ability of the aircraft to hydroplane and allow part of the structure to rise out of the water will also reduce fore-aft decelerations by reducing the area of the structure in contact with the water. The response of the structure is also dependent on the integrity of the forward and lower fuselage. Failure or extensive deformation to those areas of the structure in contact with the water will significantly increase the drag resistance to forward motion and can generate high local loads due to the applied water pressure. In high forward speed impacts these water pressures can produce substantial damage and structural failures.

In more severe impacts failure of lower fuselage panels can allow water to contact internal structural bulkheads resulting in significant increase in drag loads. Increased loads will produce greater structural distortion and further increases in load that can eventually lead to catastrophic failure and break up of the airframe.

To improve the ability of the helicopter to withstand high forward speed impacts, the aircraft must first be designed to offer a low resistance to forward motion in the water. The outer skin of the lower and forward fuselage must also be designed to withstand the applied water pressures and to minimise the probability of water entry into occupied areas. The shape of the lower forward fuselage should encourage a nose high attitude in the water (e.g. hydro planing) to reduce the area of the structure in contact with the water. One method of preventing damaging nose down pitching behaviour, induced for example by protuberances below the lower surface of the fuselage, is to incorporate a device under the nose or forward fuselage that will generate sufficient hydrodynamic lift to produce a positive nose up pitching moment.

In vertical impacts onto water, the mechanism of load distribution has been shown to be significantly different from that of land impacts. In water impacts, loads are distributed over a large area of the lower fuselage (i.e. the area in contact with water) and may produce failure of the low strength skin panels. Because the applied loads are not concentrated in the high stiffness beams and bulkheads, as in impacts onto a rigid surface, little energy absorbing deformation of these primary load paths occurs. As a result, vertical deceleration levels are generally higher than for land impacts. The high incidence of spinal injury in vertical water impacts supports this view.

In section 6 it was shown that fuselage shape can have a significant effect on decelerations generated during a vertical water impact. Although a shape may initially generate a low resistance to movement through the water, thus producing low decelerations, subsequent deformations under the applied water pressures may totally reverse the initial benefit. Controlled deformation of the lower fuselage was shown to play a significant role in reducing vertical decelerations; rigid shapes produced the higher decelerations. However, it was important to ensure that the extent and mode of deformation were controlled.

The inability of the water surface to fully support the length of the fuselage, the presence of differential water pressures along the length of the lower fuselage or a large aircraft pitch attitude on entry into water, may generate significant bending moments in the fuselage. In severe cases these bending moments may be of a sufficient magnitude to initiate bending failures in the airframe. The practice of designing helicopter main structural load paths for vertical, longitudinal and lateral crash cases only will need to be reviewed if future aircraft are to be designed to better withstand water impacts and to increase the probability of occupant survival.

The key to survival in helicopter water impacts is to design the forward and lower fuselage to withstand high water pressures and to provide a protective shell for occupants. However, the provision of a protective shell is of little value if seat strengths and restraint systems are inadequate to withstand the decelerative forces on impact and allow the occupants to flail around inside the cabin. As discussed earlier, failure of passenger seats in civil helicopters has been shown to be a major factor contributing to occupant injuries and loss of life. The last revision of FAR Part 29 (amendment 29–29, effective 12/3/89) and the first issue of JAR–29 requirements (effective 5/11/93) covering the design of helicopter structures and seats for emergency landing, call for significant increases in static inertia factors over those employed in current designs. The dynamic testing of all civil helicopter seats and the fitment of upper torso restraints are now also specified. It is considered that the improved levels of occupant restraint provided by these measures will provide a significant improvement in occupant safety.

Maintaining a protective shell and ensuring that occupants are fully restrained during an impact, however, will not provide adequate protection if the helicopter subsequently inverts or sinks. As drowning is the major cause of fatalities in helicopter water impacts for both military and civil helicopters, design techniques to improve the probability of the aircraft remaining afloat after impact for long enough for the occupants to escape, should be the primary objective. Design measures to reduce the vulnerability of flotation systems to structural damage should be given particular attention. The use of internal (and hence less vulnerable) flotation aids fitted into empty fuselage bays and rear fuselage, for example, should also be considered.

Work is currently in progress by the US Navy and the Federal Aviation Administration to analyse impulsive hydrodynamic loading on helicopter airframes and to develop approaches to enhance structural capability. A series of full scale helicopter crash tests is also being planned by the US Navy to validate these analyses. This work will provide valuable knowledge to improve the survivability of water impacts for future designs.

9 CONCLUSIONS

(i) The primary cause of loss of life in military and civil helicopter water impacts over the period 1971–1992 was drowning. Occupant fatalities resulting from excessive crash forces or as a result of structural collapse during impact were a secondary issue.

(ii) Structural loads and occupant injury probability in helicopter water impacts are dependent on both impact velocity and the behaviour of the structure on entry into water. It is the water pressure generated on contact with a water surface, rather than inertial forces that will determine the structural response and occupant survival.

(iii) Designing the lower fuselage of the helicopter to withstand water pressures without excessive deformation and without water entry into the internal structure or occupied areas is the key issue in designing to survive water impacts. At present, however, there are no requirements that call for the airframe to be so designed.

(iv) The major cause of drowning is the inability of occupants to escape from an inverted or submerged helicopter. Disorientation due to an inrush of water, inability to locate or open exits and incapacitation due to injuries are the main reasons for the inability to escape.

(v) Design techniques for increasing the capability of the helicopter structure to remain afloat after impact with water for long enough for occupants to escape, is considered to be the major factor in improving occupant survival. Current military and civil airworthiness requirements, however, do not consider water impacts as a crash case and as a result, flotation systems are only required to withstand a controlled alighting onto water. Recognition of water impacts as a representative and realistic crash case is seen as the first step in improving occupant safety.

(vi) Although only briefly investigated in this study, mathematical modelling techniques are considered to be a potentially valuable tool in the analysis of aircraft structural behaviour on impact with water. However, validation of these techniques, against for example experimental data, would be required before they could be considered for use as a design tool.

10 ACKNOWLEDGEMENTS

Information and photographs of UK civil helicopter accidents are presented here with permission of the Department of Transport, Air Accidents Investigation Branch, Royal Aerospace Establishment, Farnborough. For the UK military helicopter accidents reviewed in this report, information and photographs are presented with the permission of the RN Aircraft Accident Investigation Unit, HMS Daedalus, Lee-on-Solent, Hants. Valuable additional information and support has been provided by personnel from both accident investigation establishments. These contributions are gratefully acknowledged.

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List of Figures

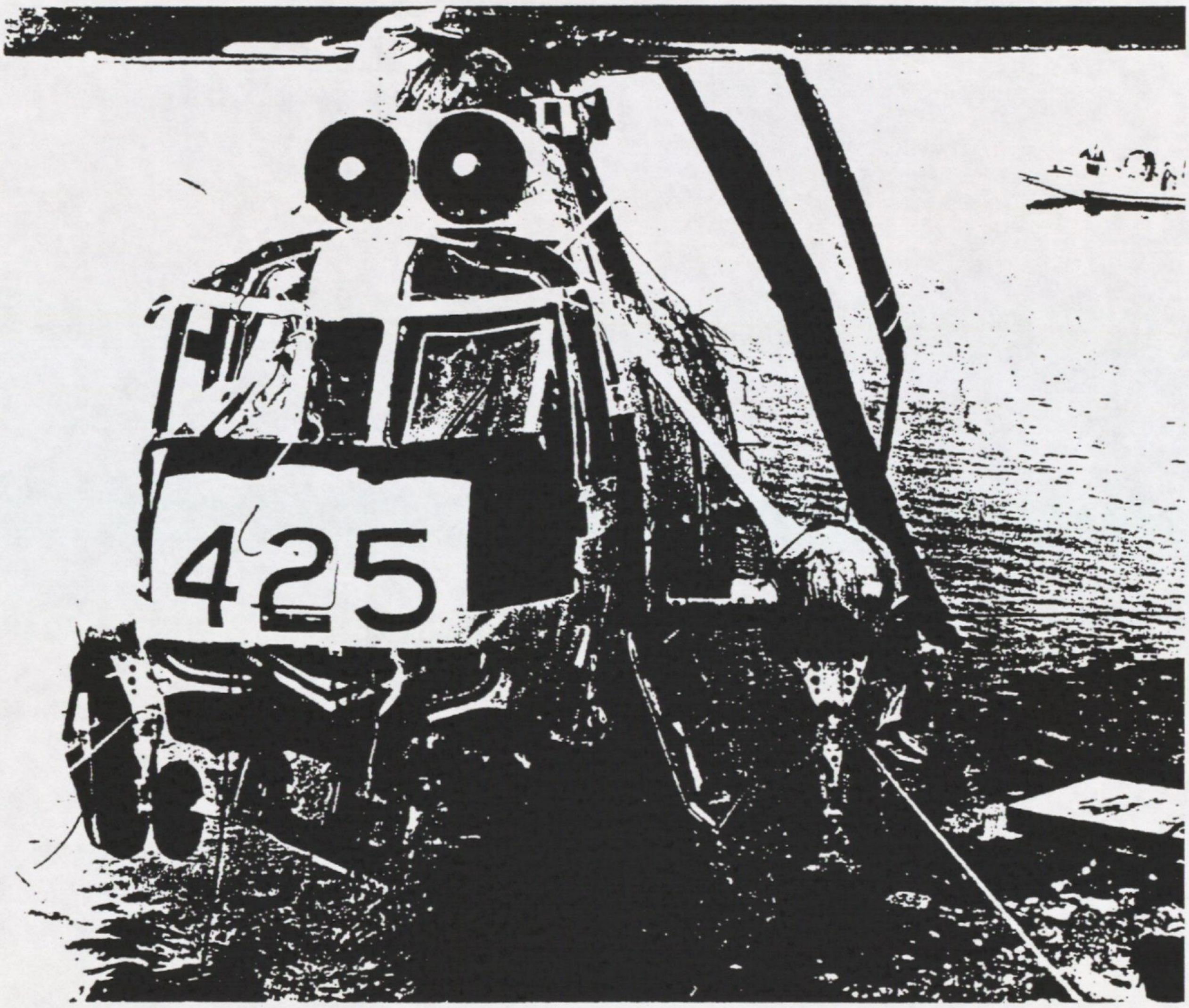
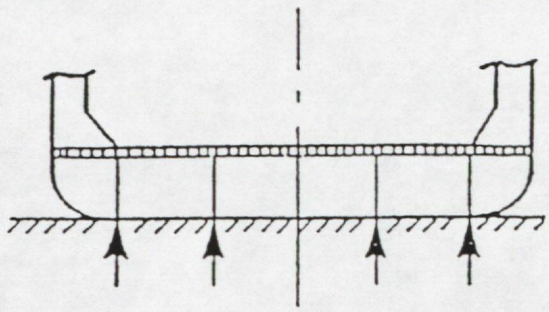


Figure 1 **Damage to Canadian S61 following impact with water (from Brooks Ref. 10)**

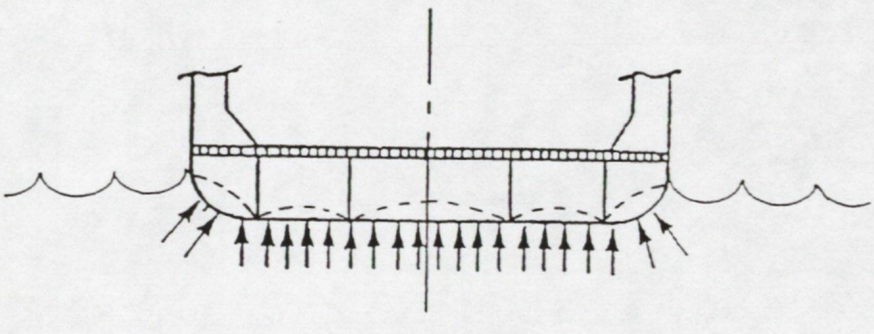
GROUND IMPACT



CONCENTRATED LOAD IN PRIMARY LOAD STRUCTURE

- KEEL BEAMS AND FRAMES ARE HIGHLY LOADED
- CONTROLLED DEFORMATION ABSORBS ENERGY

WATER IMPACT



UNIFORMLY DISTRIBUTED LOAD

- SKINS LIGHTLY LOADED
- SKIN FAILURE REDUCES ENERGY ABSORBING CAPABILITY OF UNDERFLOOR STRUCTURE
- WATER PRESSURES CAN DISRUPT FLOOR

Figure 2 Structural effects of vertical impact with water

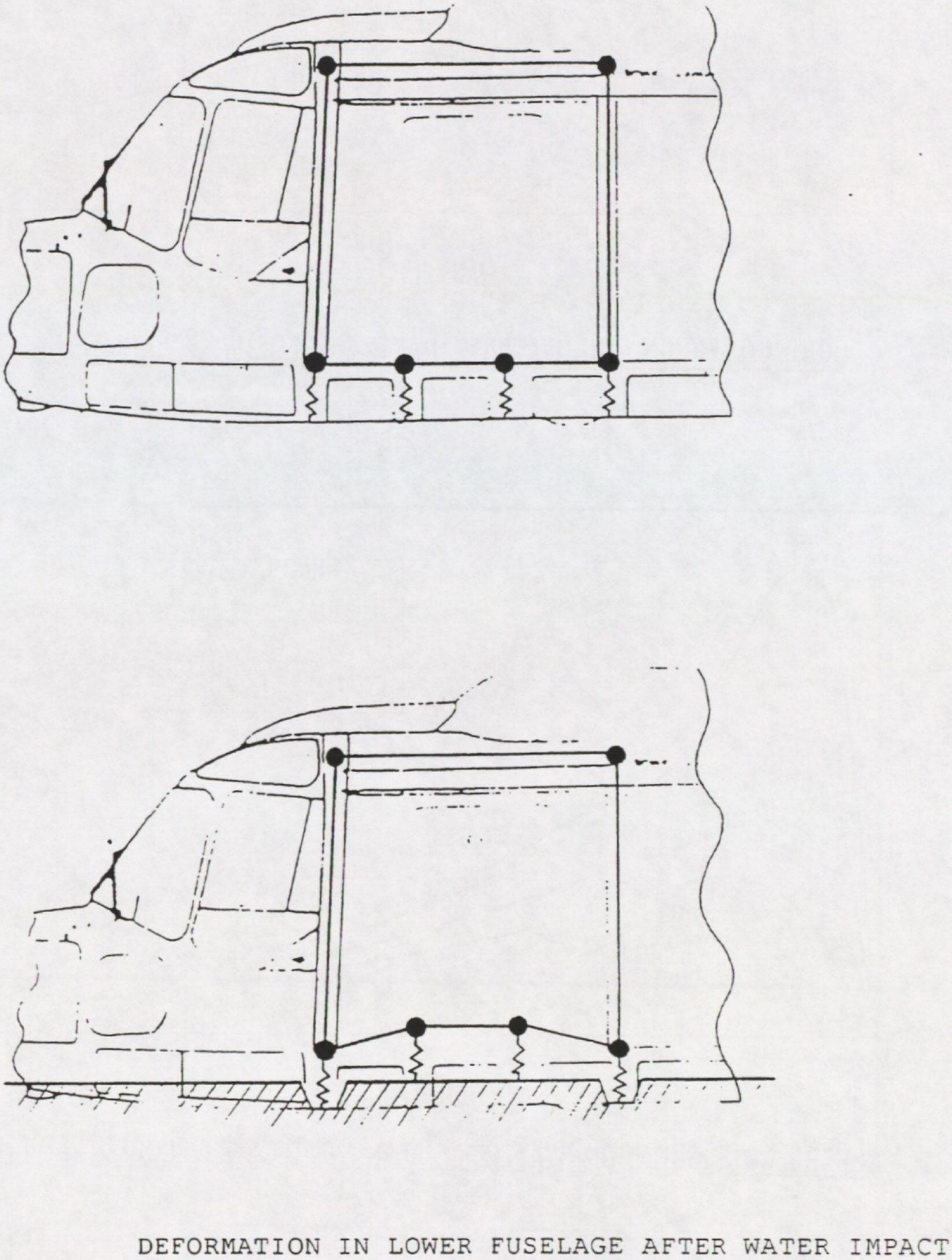
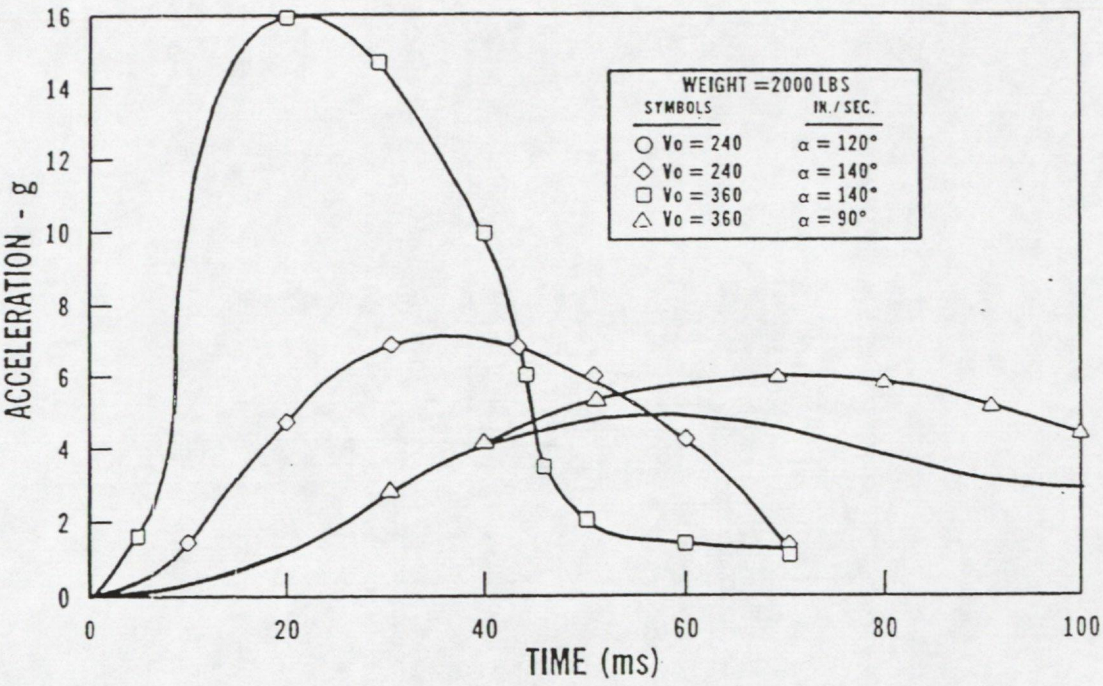
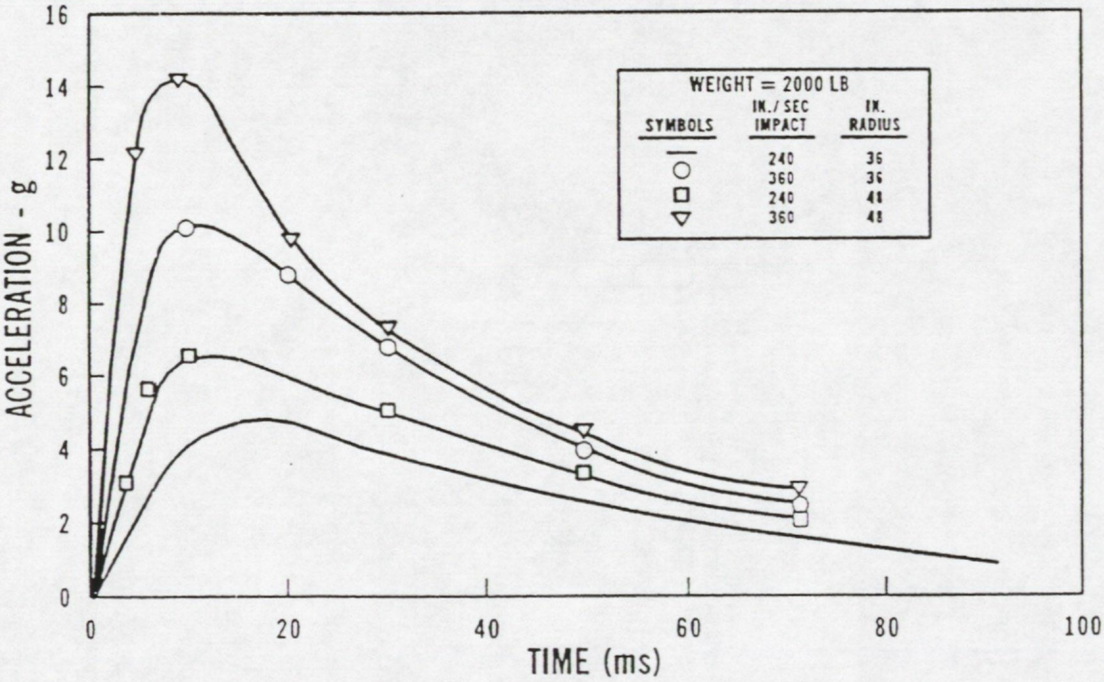


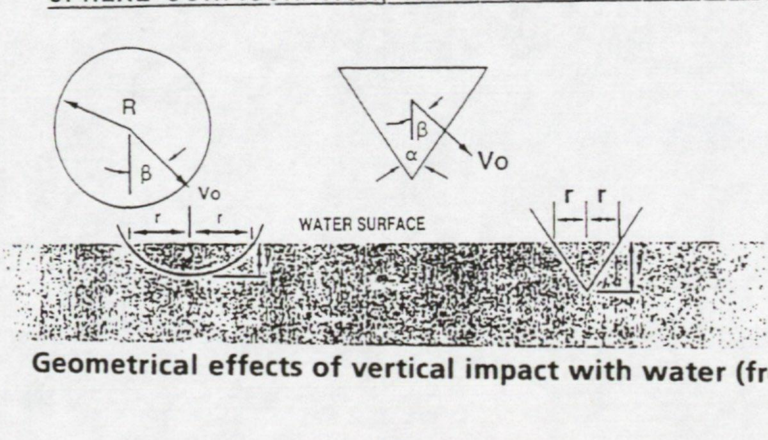
Figure 3 **KRASH model of fuselage section before and after a simulated vertical impact with water (from Clifford Ref. 5)**



CONE CONFIGURATION. WATER IMPACT - VELOCITY, α VARIATION



SPHERE CONFIGURATION, WATER IMPACT - RADIUS & VELOCITY VARIATION



BODY GEOMETRIES

Figure 4 Geometrical effects of vertical impact with water (from Wittlin Ref. 29)

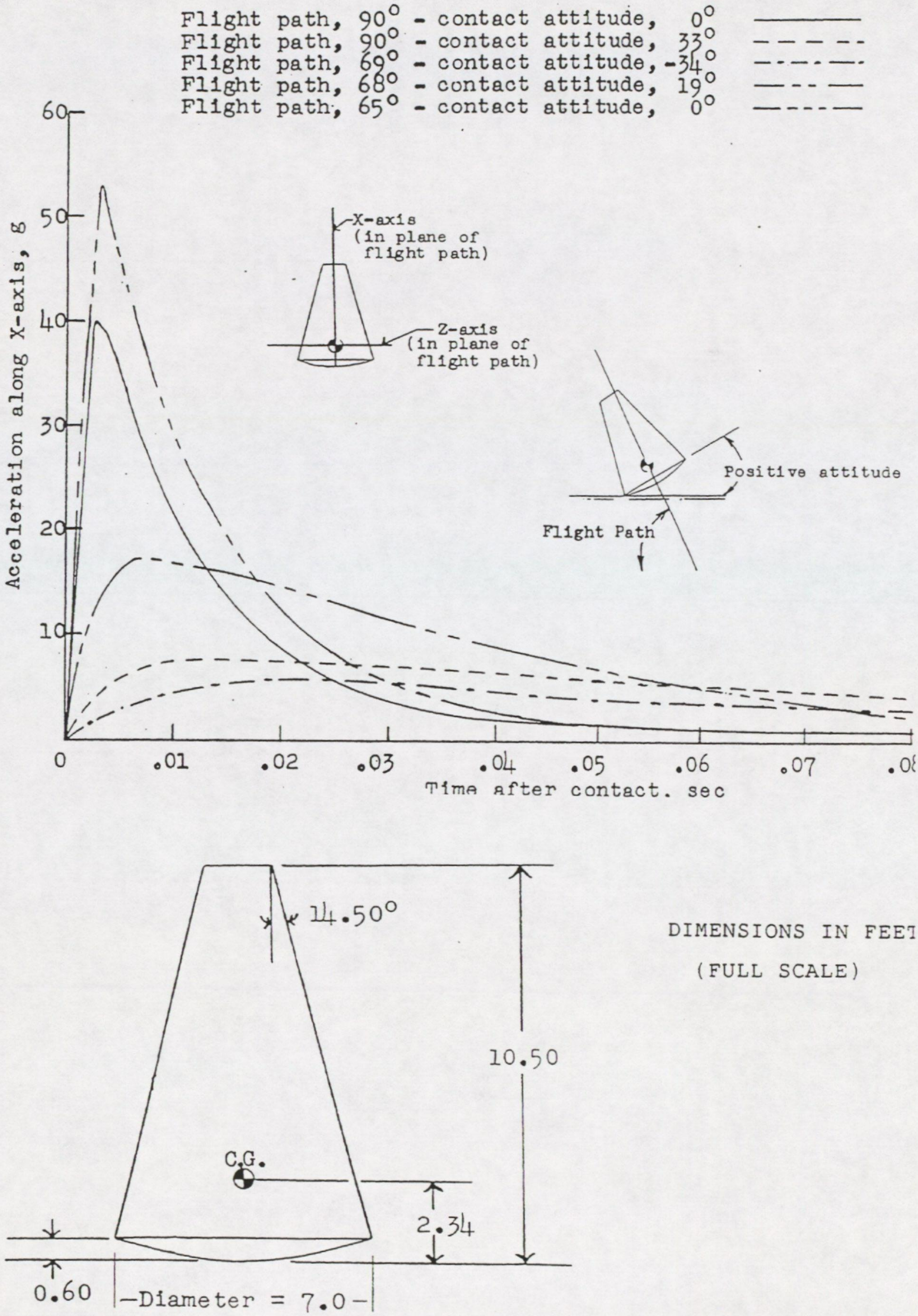
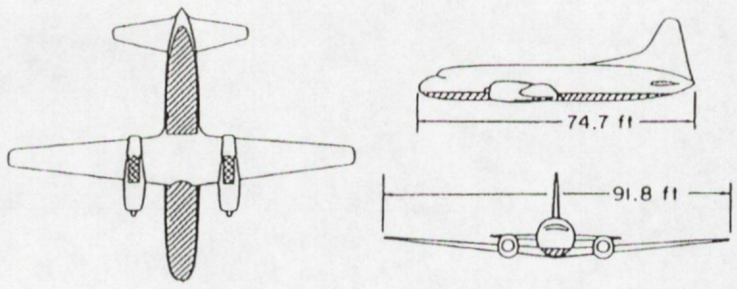


Figure 5 Acceleration – time histories for model re-entry vehicle drop test into water (from Ref. 30)

SUMMARY OF MODEL-DITCHING INVESTIGATION OF TRANSPORT

Damage simulated by use of scale-strength parts (hatched areas) and removal of other parts (crosshatched areas).



Landing attitude, deg	Flap setting, deg	Landing speed, knots	Length of run, ft	Maximum longitudinal deceleration, g units	Average longitudinal deceleration, g units	Motions of model (*)
Undamaged model						
1	0	164	850	4	1½	u h
1	39	100	350	5	1½	u h
5	0	122	650	3	1	u h
5	39	88	400	1½	1	h
9	0	105	600	3½	1	h
9	39	82	400	1	½	h
Damaged model						
5	0	122	250	8	2½	h b
5	39	88	300	3½	1	h
9	0	105	300	6	1½	h
†9	39	82	300	3	1	h

*In this column, the letters indicate the following motions:

b ran deeply—the model settled deeply into the water with little change in attitude

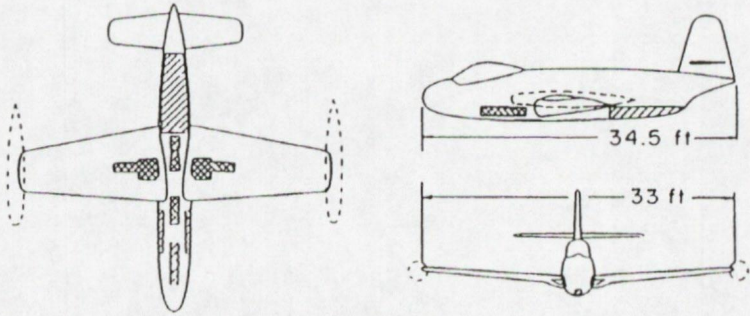
h ran smoothly—the model made a very stable run

u trimmed up—the attitude of the model increased while running in the water

†Recommended ditching attitude and flap setting.

SUMMARY OF MODEL-DITCHING INVESTIGATION OF FIGHTER

Damage simulated by use of scale-strength parts (hatched areas) and removal of other parts (crosshatched areas).



Landing attitude, deg	Flap setting, deg	Landing speed, knots	Length of run, ft	Maximum longitudinal deceleration, g units	Average longitudinal deceleration, g units	Motions of model (*)
Undamaged model						
4	27	124	500	2	1½	u s p
8	27	107	550	1	1	u s p
12	27	97	400	2	1	u p
Damaged model						
4	27	124	200	9	3½	p d_2
8	27	107	150	10	3½	d_1
†12	27	97	100	7	4	d_1

*In this column, the letters indicate the following motions:

d_1 dived violently—the model stopped abruptly in a nose-down attitude with most of the model submerged

d_2 dived slightly—the model stopped abruptly in a nose-down attitude with the nose of the model submerged

p porpoised—the model undulated about the transverse axis with some part of the model always in contact with the water

s skipped—the model rebounded from the water

u trimmed up—the attitudo of the model increased while running in the water

†Recommended ditching attitude and flap setting

Figure 6 **Effect of lower fuselage structural integrity on ditching performance (from Ref. 35)**

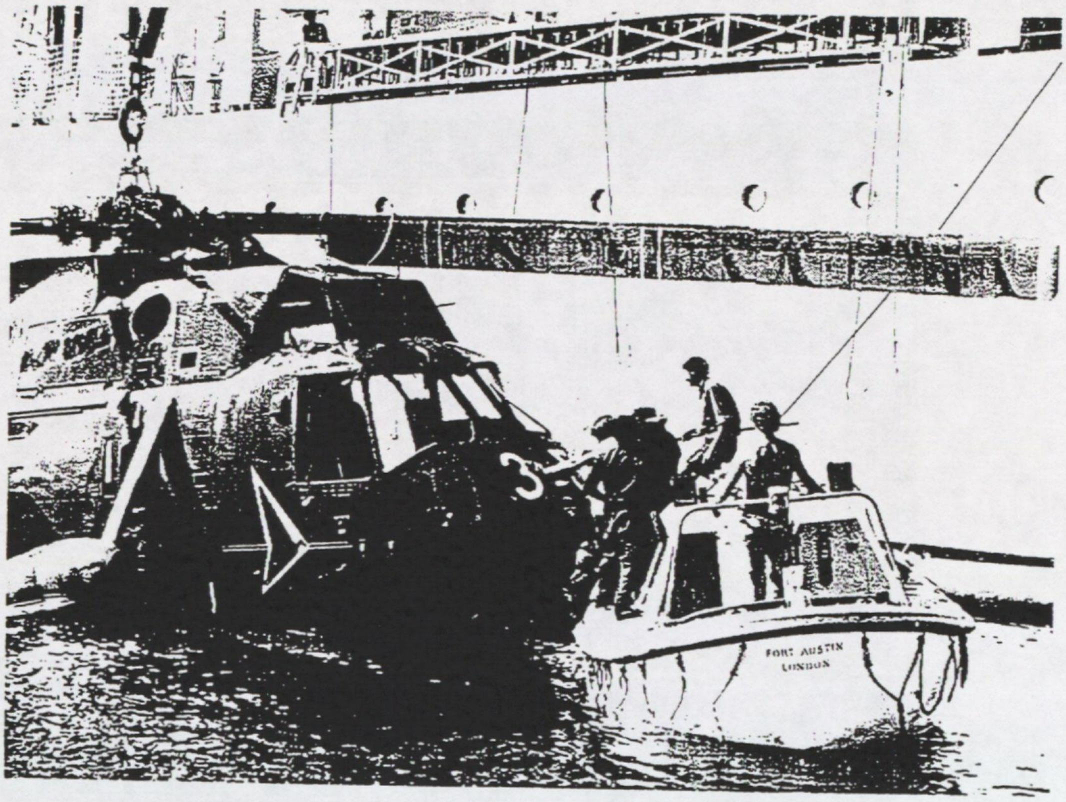


Figure 7 A Navy Sea King being recovered from the sea following a controlled ditching

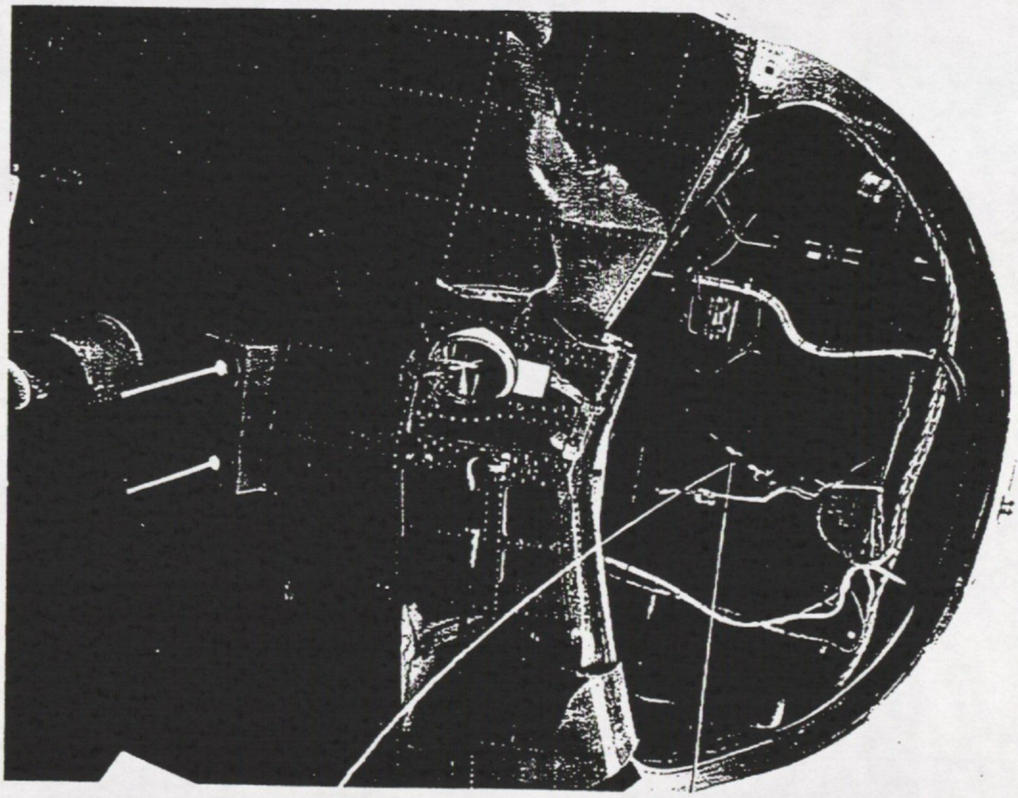


Figure 8 Damage to lower fuselage of a Sea King helicopter showing loss of electronics bay door

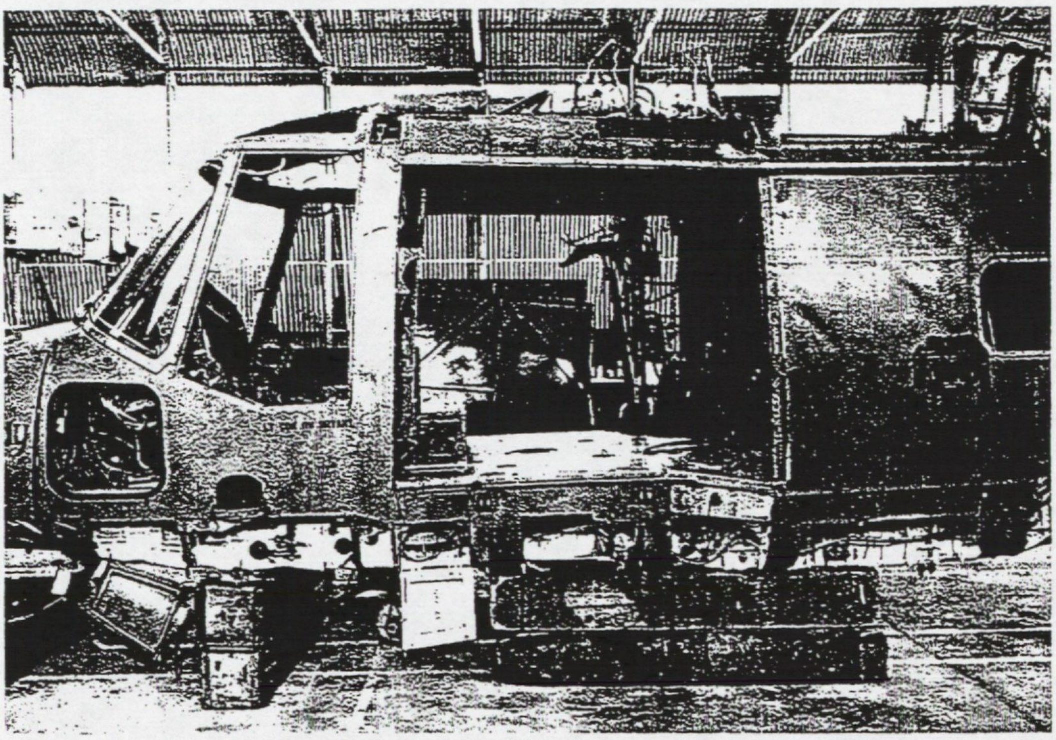


Figure 9 **Damage to main cabin of a Navy Lynx helicopter following a vertical descent with limited control**

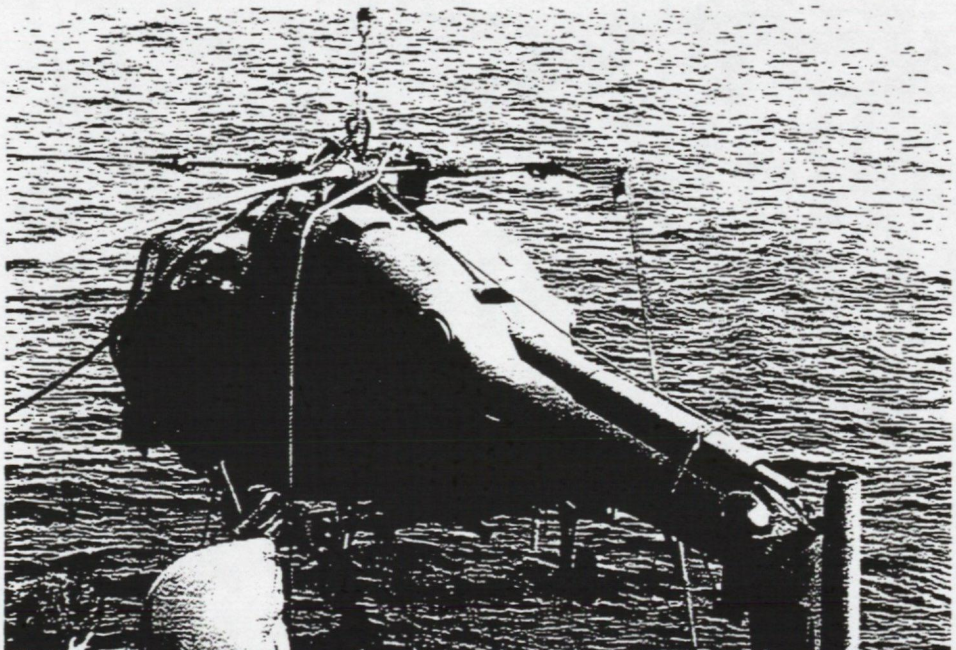


Figure 10 **Damage to rear fuselage of the Lynx helicopter shown in Figure 9**

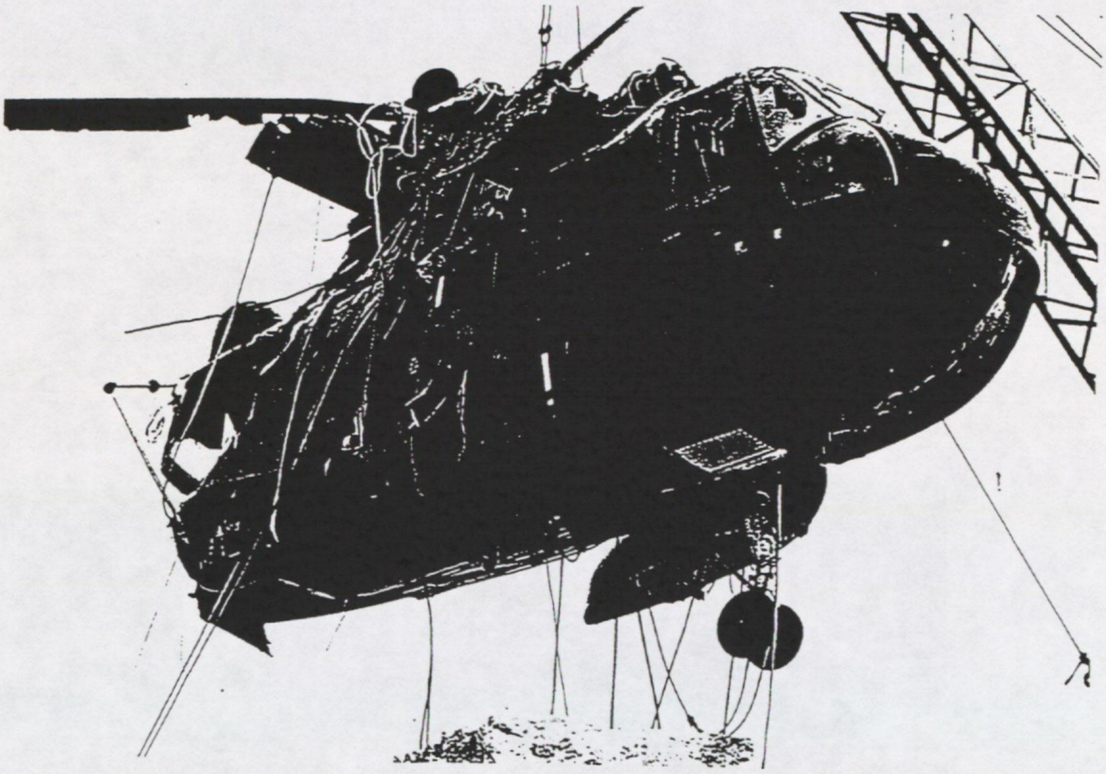


Figure 11 A Navy Sea King being recovered following a descent with limited control

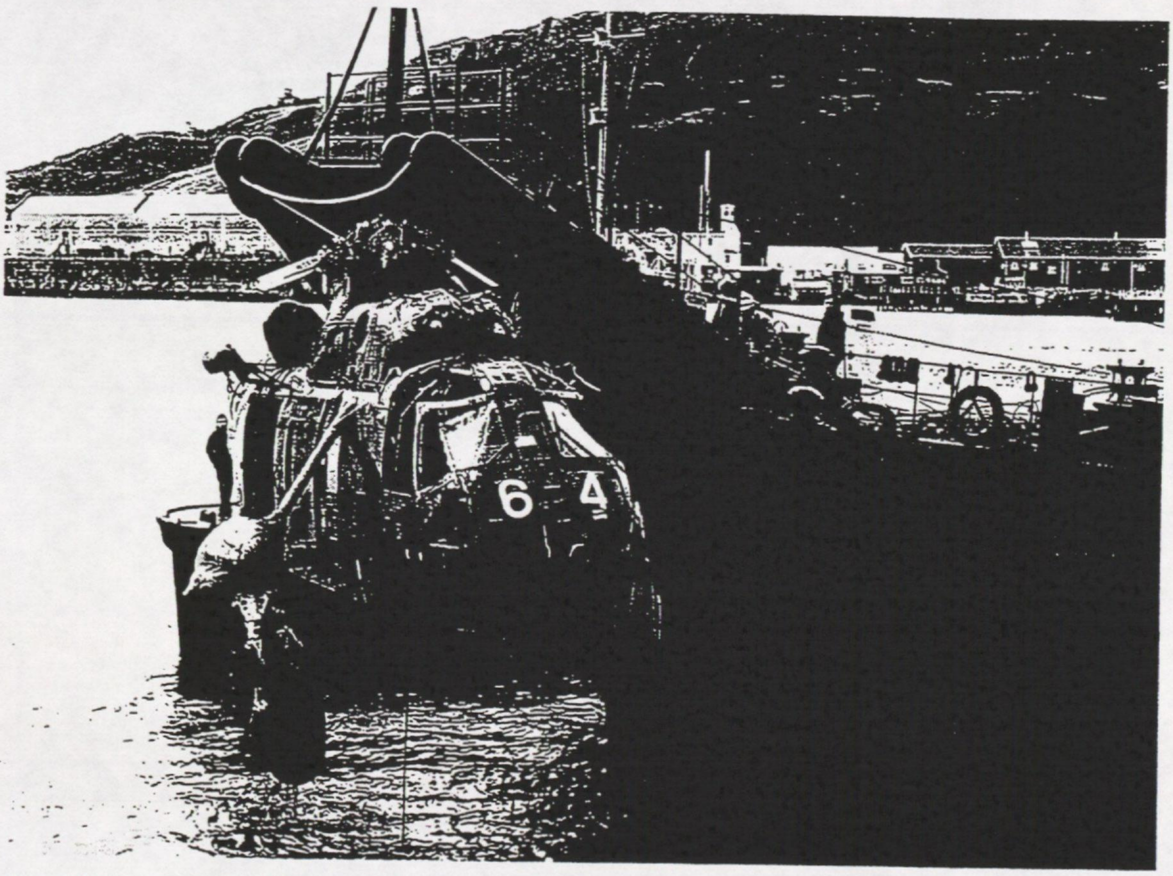
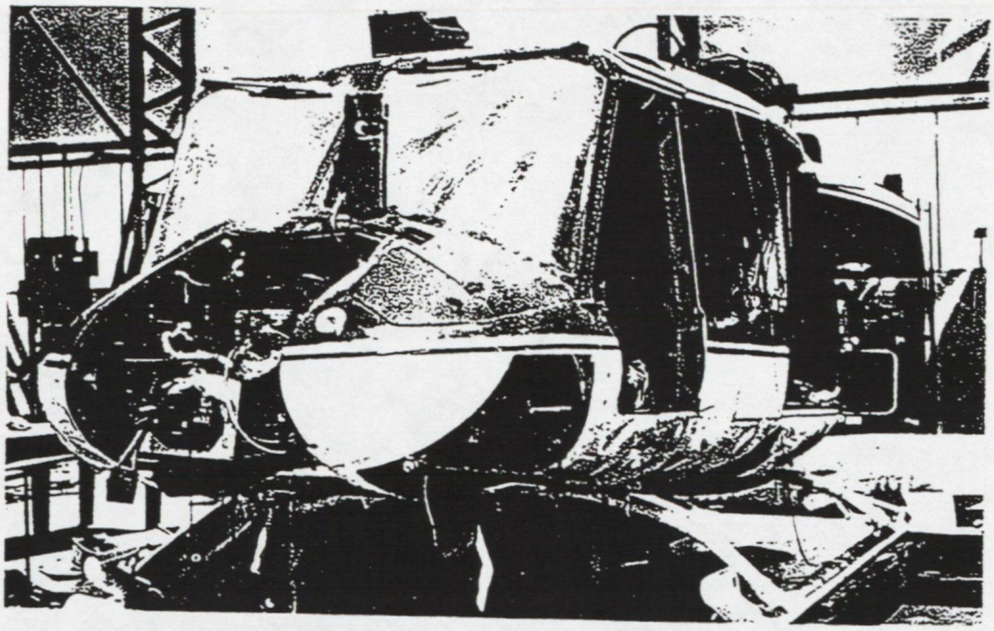
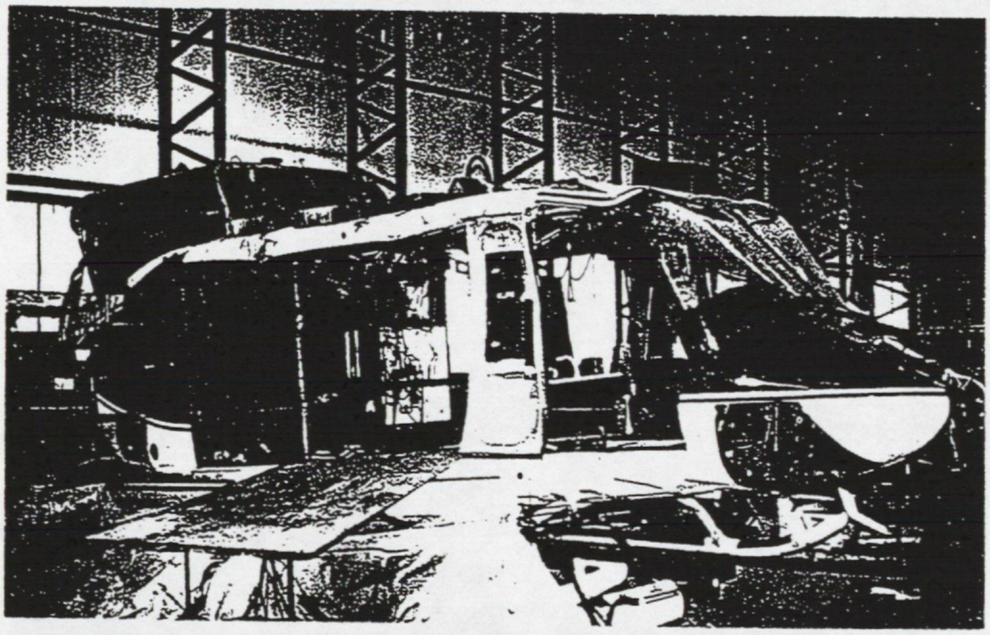


Figure 12 Damage to a Sea King helicopter following a limited control descent

A



B



C

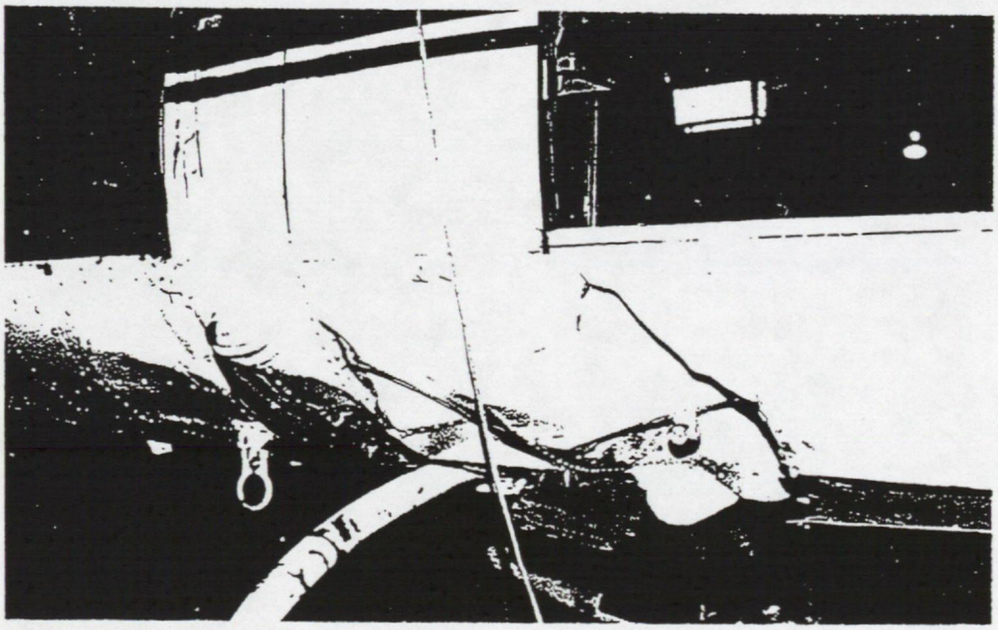


Figure 13 Damage to a Bell 212 following a limited control descent

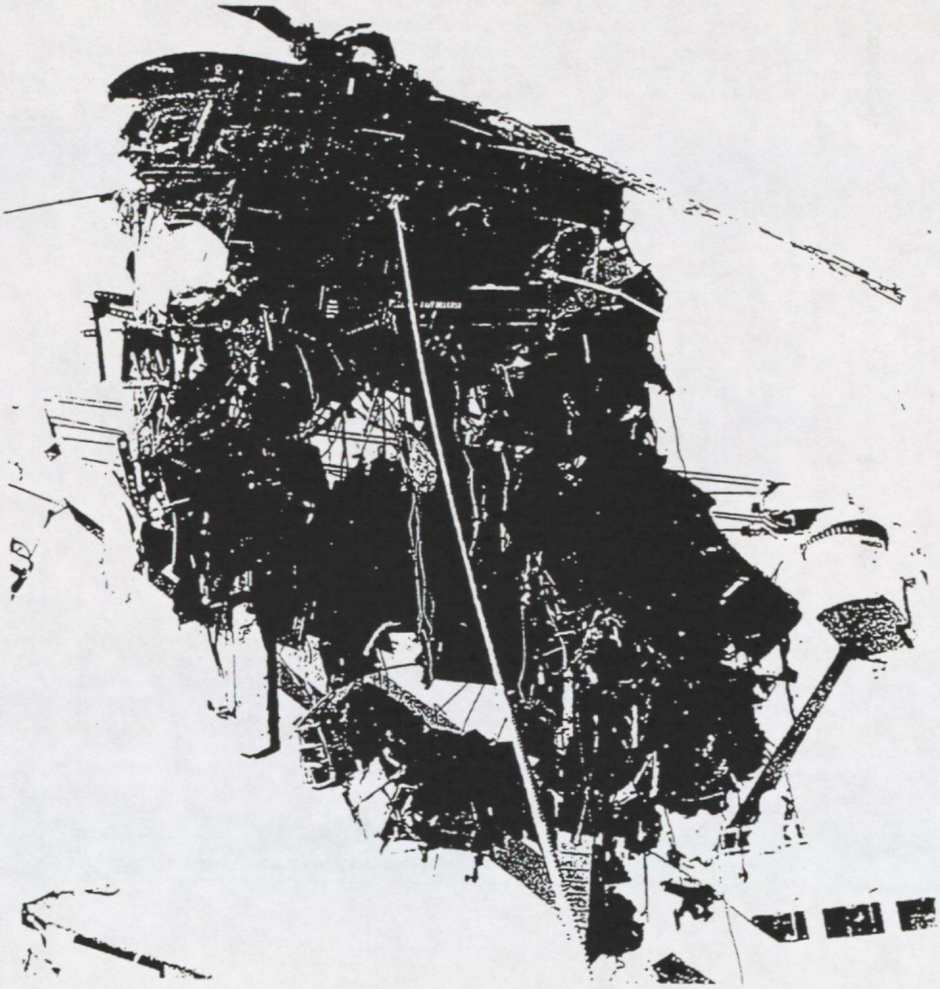


Figure 14 Breakup of a Sea King helicopter following a high forward speed fly-in water impact

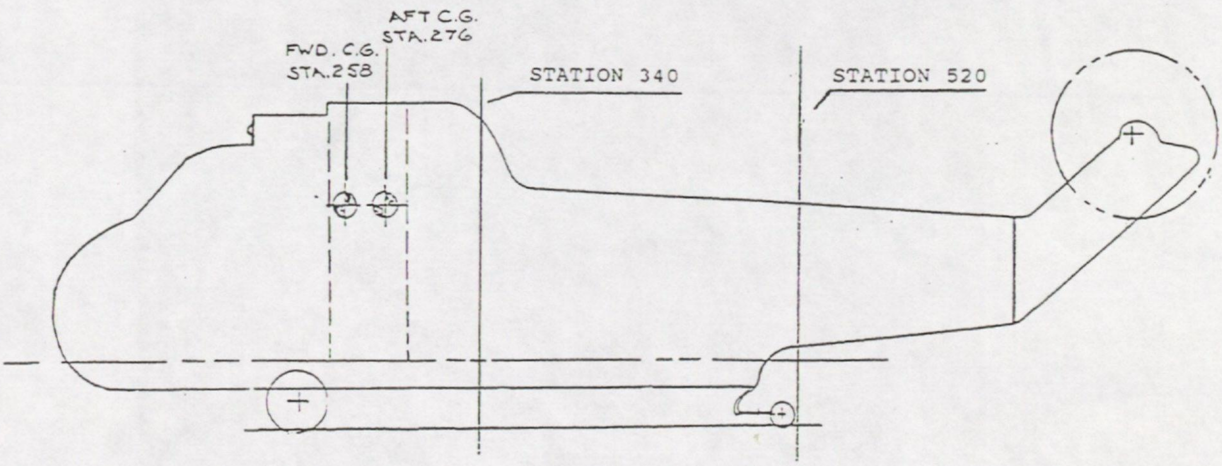


Figure 15 Position of airframe failures for the accident shown in Figure 14

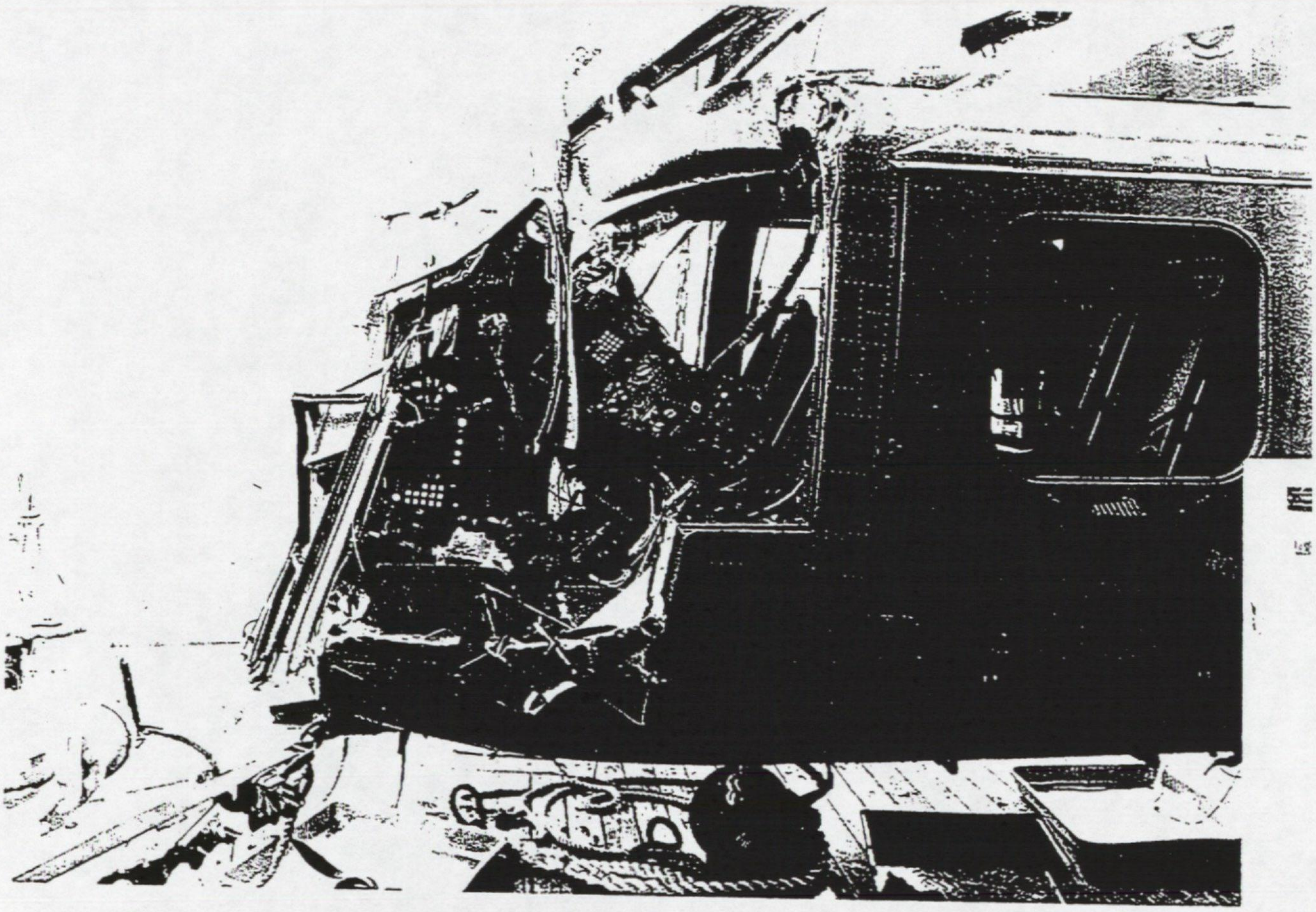


Figure 16 Damage to forward fuselage of a Navy Lynx following a fly-in water impact

Figure 17 Underside of fuselage for the Navy Lynx shown in Figure 16

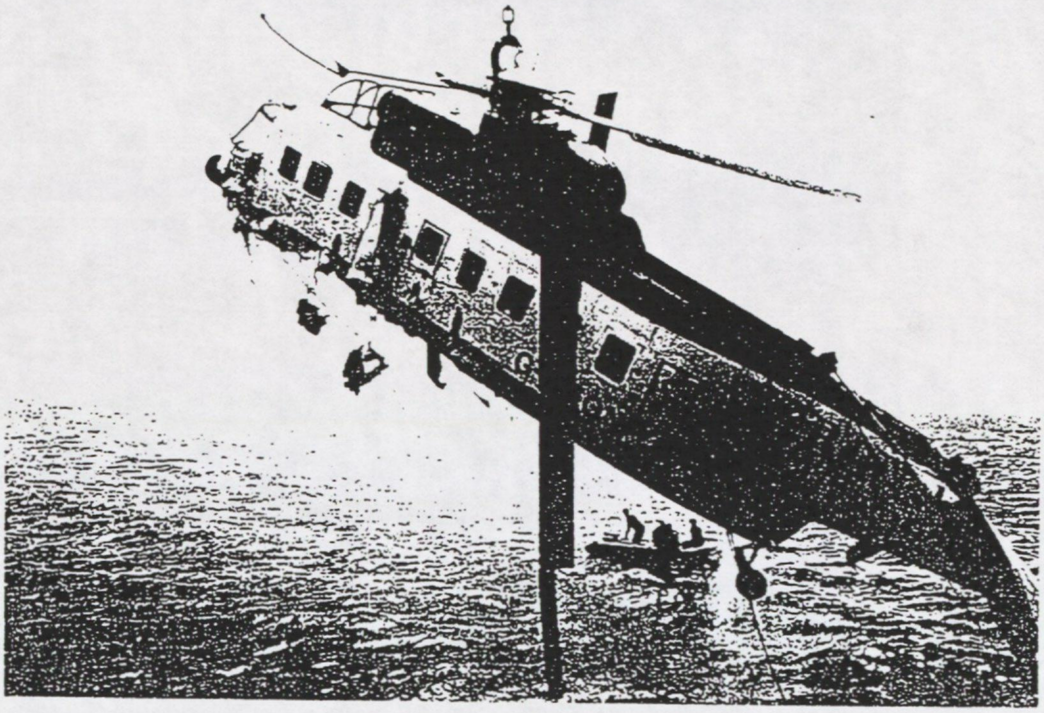


Figure 18 Recovery of a civil S61N helicopter following a high forward speed fly-in water impact

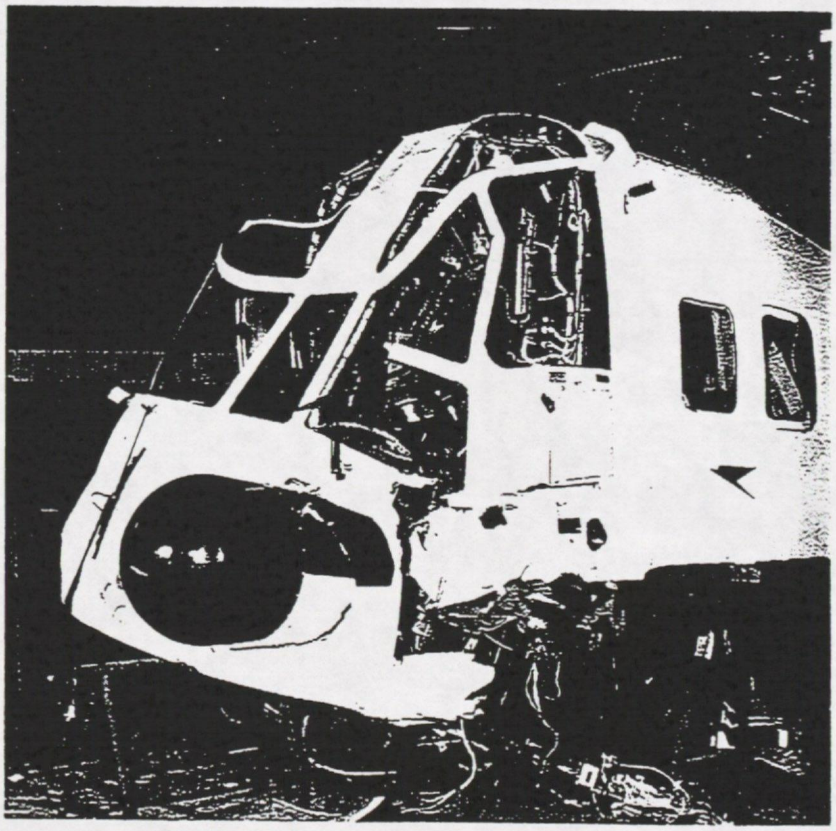


Figure 19 Damage to the forward fuselage for the accident shown in Figure 18

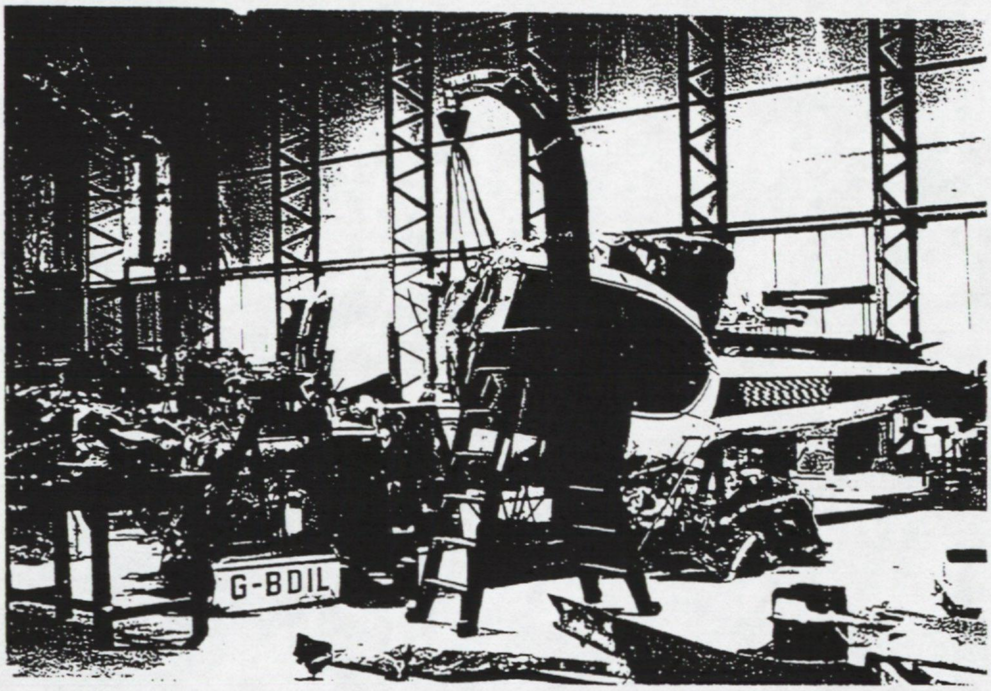


Figure 20 **Structural damage to a Bell 212 following a high forward speed fly-in accident**

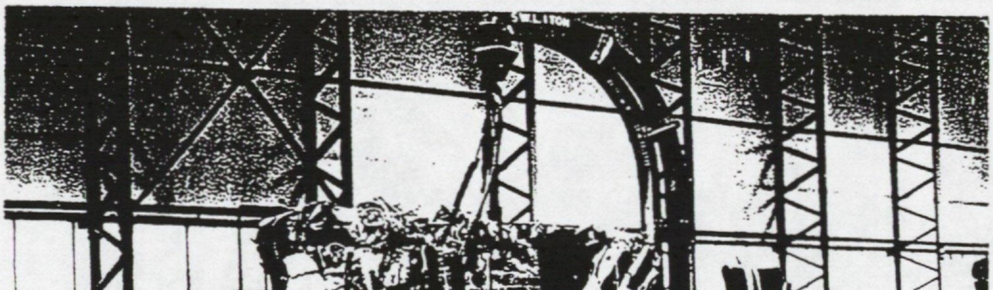


Figure 21 **Starboard view of the accident in Figure 20 showing catastrophic fuselage failure**

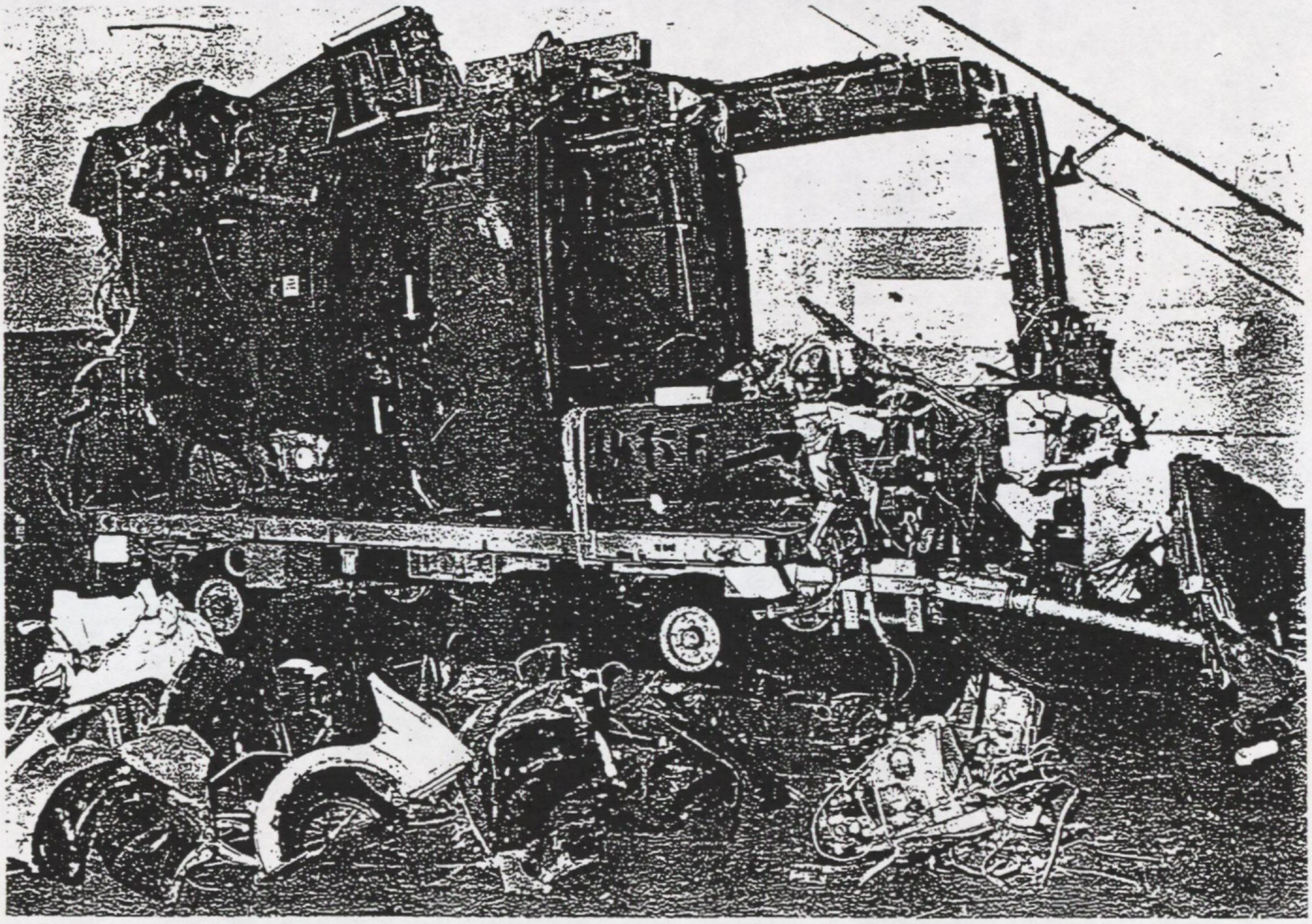


Figure 22 **Structural damage to a Navy Lynx following a high forward speed fly-in accident**

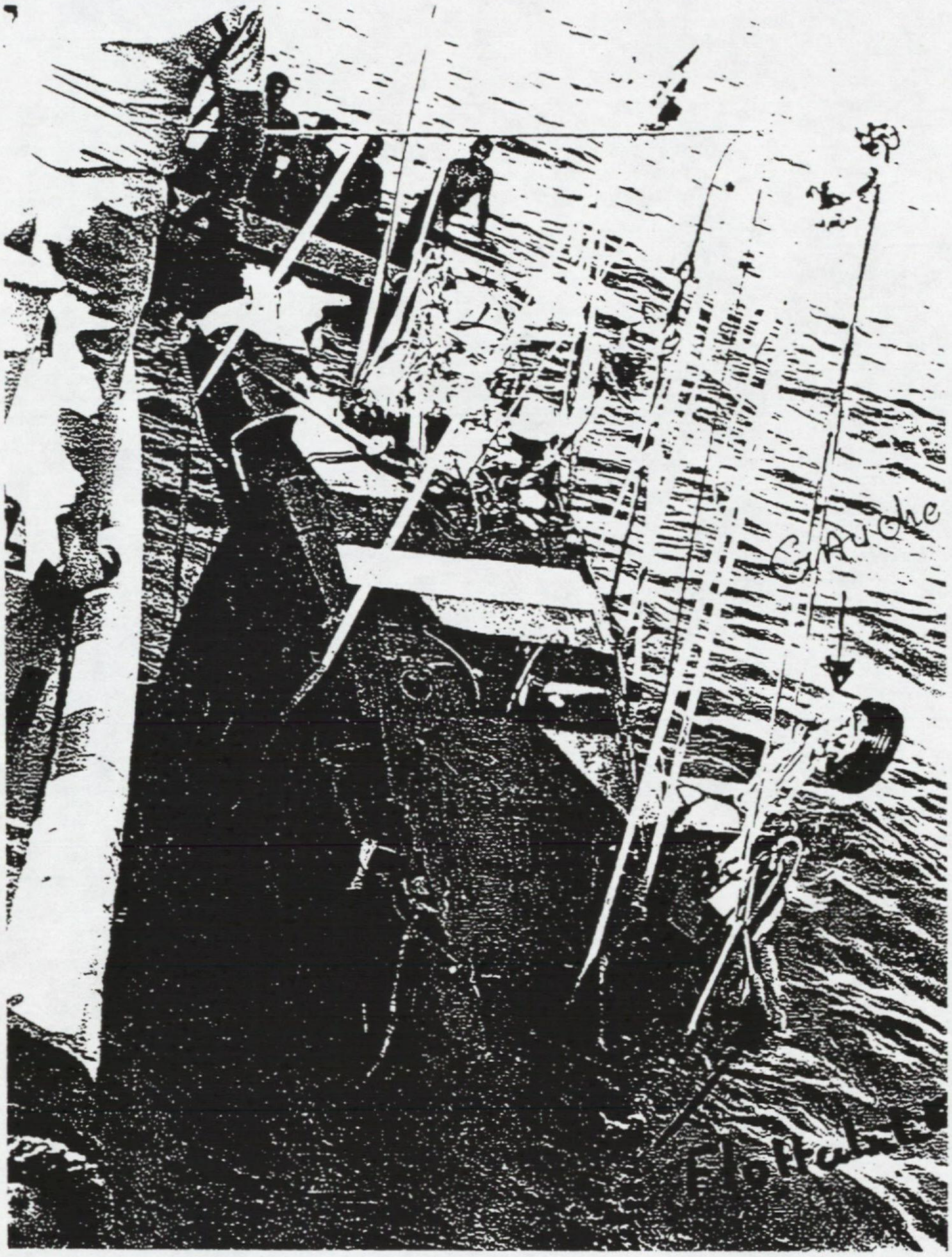


Figure 23 Lower surface of the aircraft shown in Figure 22

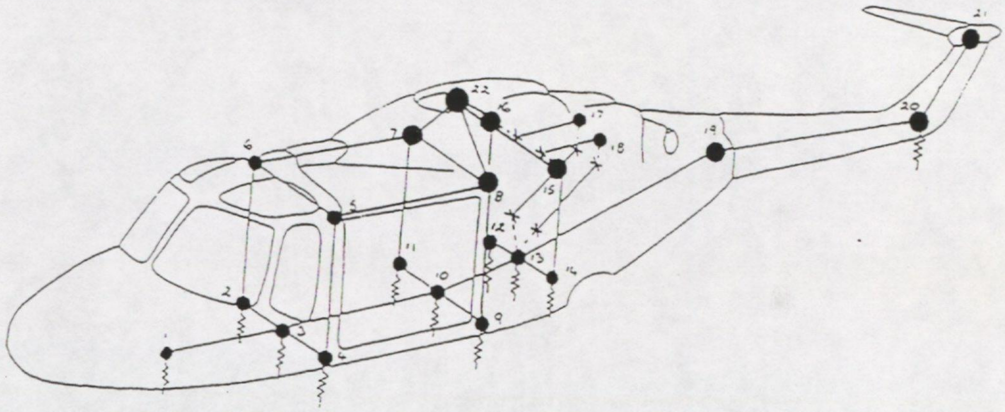


Figure 24 Lynx krash model (from Ref. 5)

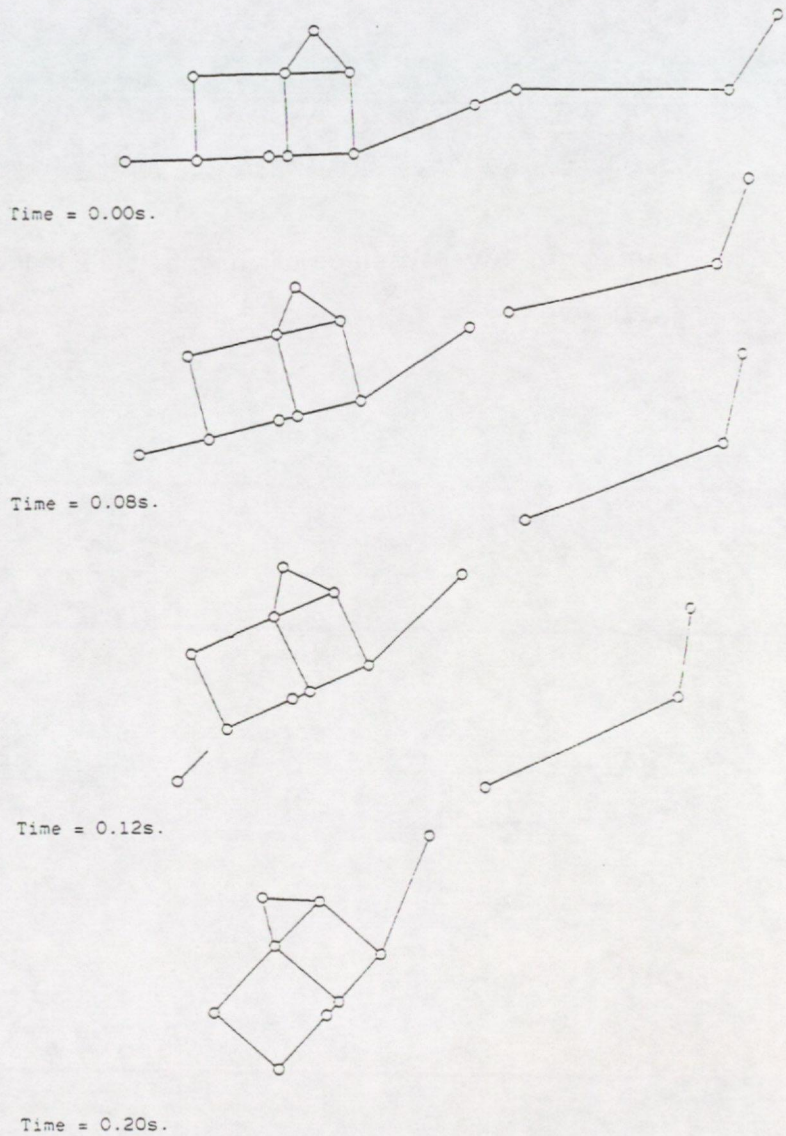


Figure 25 KRASH prediction of a high forward speed fly-in accident (from Ref. 5)

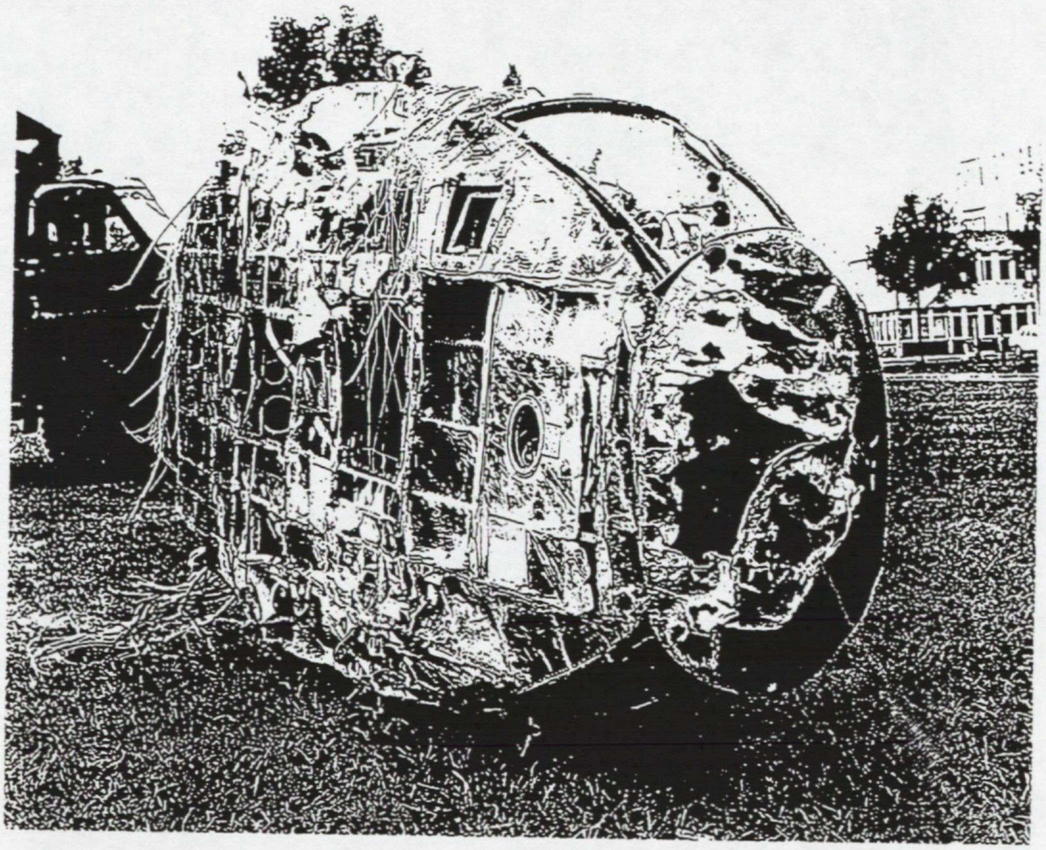


Figure 26 Damage to lower fuselage of an Army Lynx helicopter

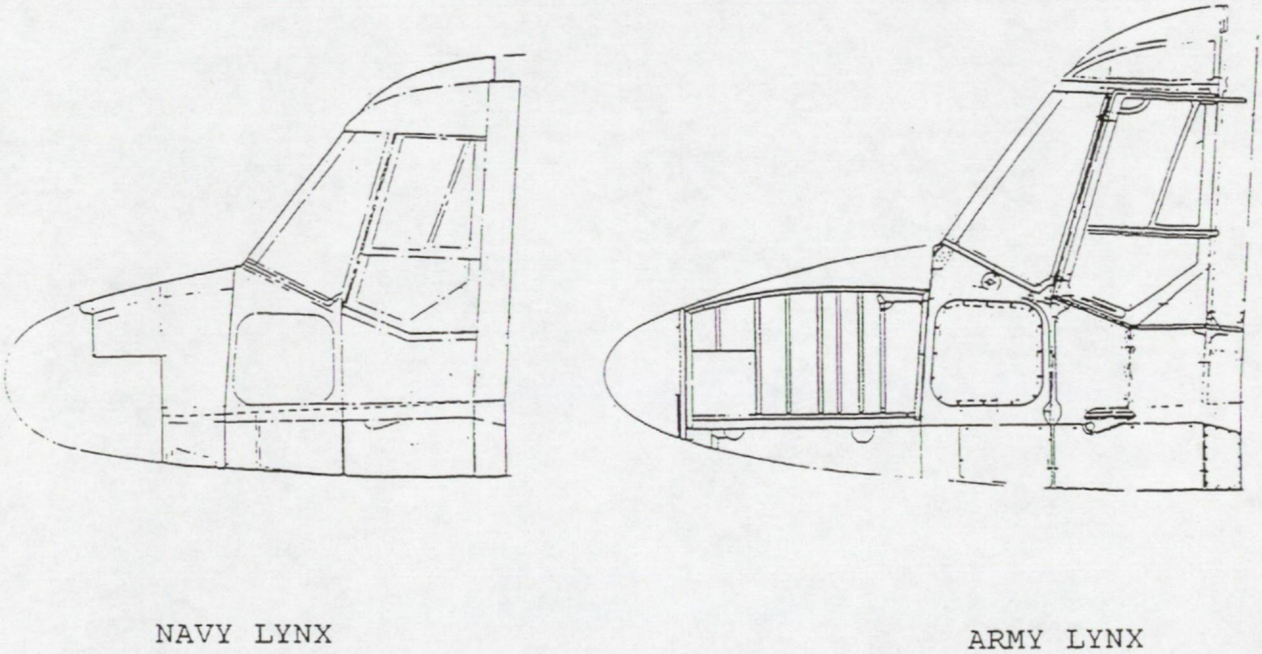
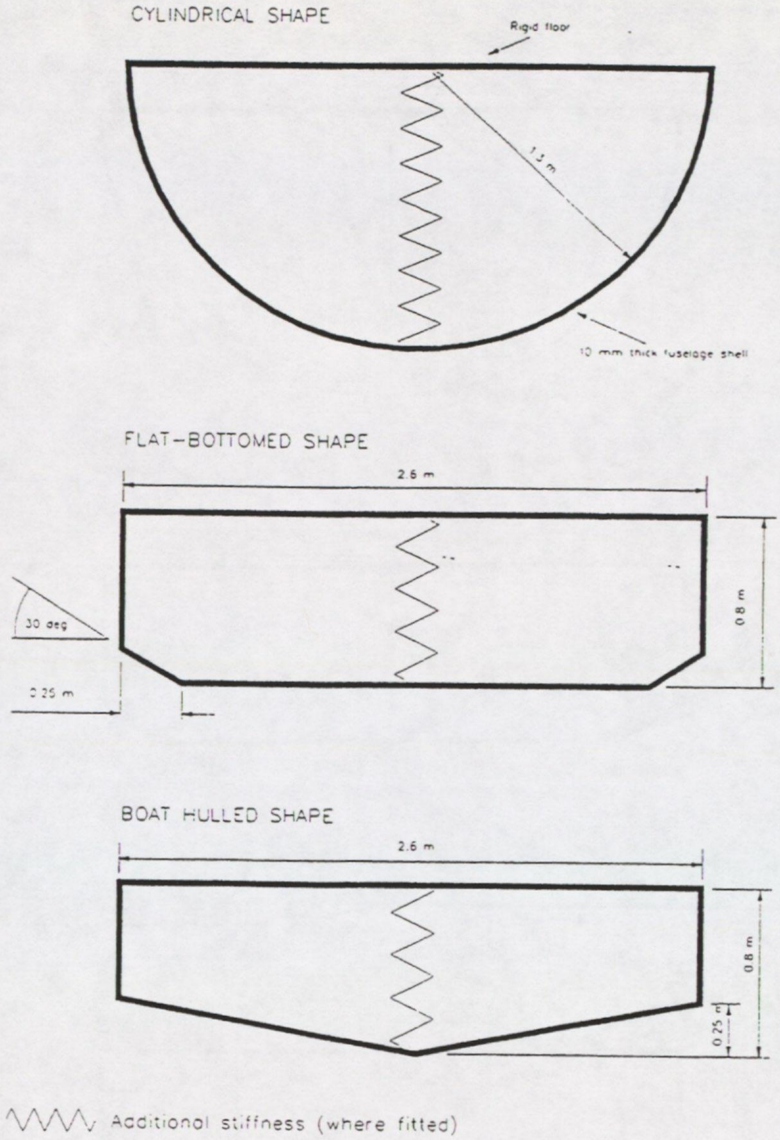
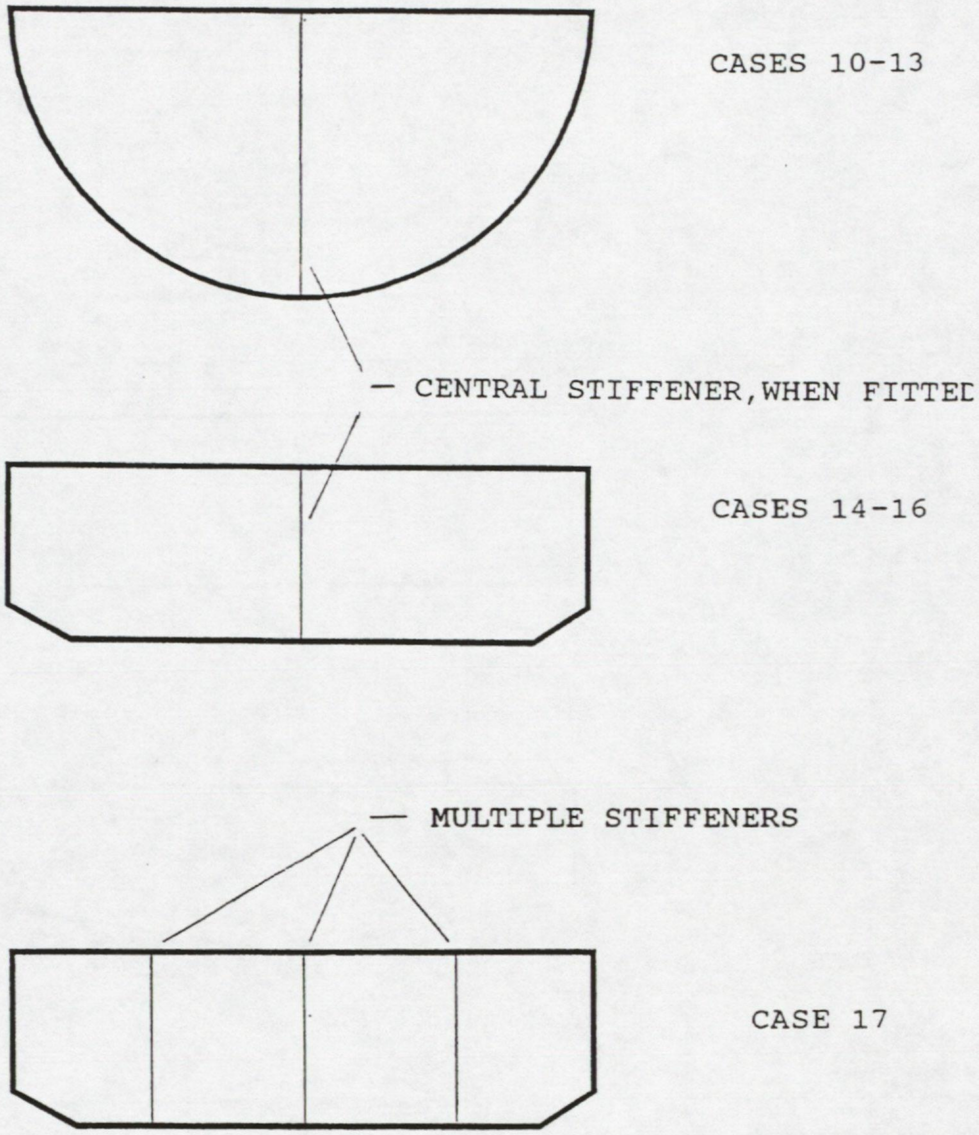


Figure 27 Forward fuselage configurations for Army and Navy Lynx helicopters



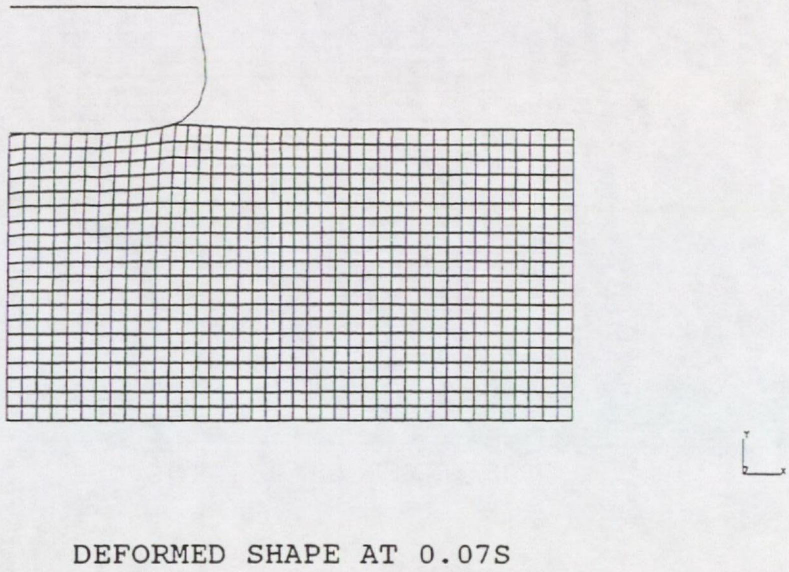
Case	Shape	Material	Additional Stiffness	Peak Vertical Floor Deceleration	Floor Vertical Displacement at Peak 'g'
1	Cylinder	Rigid	No	10.6g at 0.01s	0.05m
2	Cylinder	Elastic-Plastic	No	4.9g at 0.07s	0.48m
3	Cylinder	Elastic-Plastic	Yes	7.6g at 0.08s	0.45m
4	Flat-Bottom	Rigid	No	17.9g at 0.01s	0.05m
5	Flat-Bottom	Elastic-Plastic	No	11.1g at 0.11s	0.6m
6	Flat-Bottom	Elastic-Plastic	Yes	8.8g at 0.02s	0.15m
7	Boat Hull	Rigid	No	14.9g at 0.01s	0.1m
8	Boat Hull	Elastic-Plastic	No	12.5g at 0.11s	0.67m
9	Boat Hull	Elastic-Plastic	Yes	11.7g at 0.04s	0.3m

Figure 28 Generic helicopter shapes used in Frazer-Nash Consultancy DYNA3D analyses and summary of floor decelerations (from Ref. 43)



Case	Shape	Impact Surface	Additional Stiffness	Peak Vertical Floor Deceleration	Floor Vertica Displacement at Peak 'g'
10	Cylinder	Water	No	4.1g at 0.07s	0.5m
11	Cylinder	Water	Yes	5.3g at 0.05s	0.3m
12	Cylinder	Water	Yes	8.1g at 0.05s	0.3m
13	Cylinder	Rigid Ground	Yes	7.9g at 0.12s	0.58m
14	Flat-bottom	Water	Yes	9.1g at 0.02s	0.15m
15	Flat-bottom	Water	Yes	12.3g at 0.02s	0.12m
16	Flat-bottom	Water	Yes	7.5g at 0.02s	0.13m
17	Flat-bottom	Water	Yes(x3)	11.1g at 0.02s	0.13m

Figure 29 Generic helicopter shapes used in MSC/DYNA analysis and summary of floor decelerations



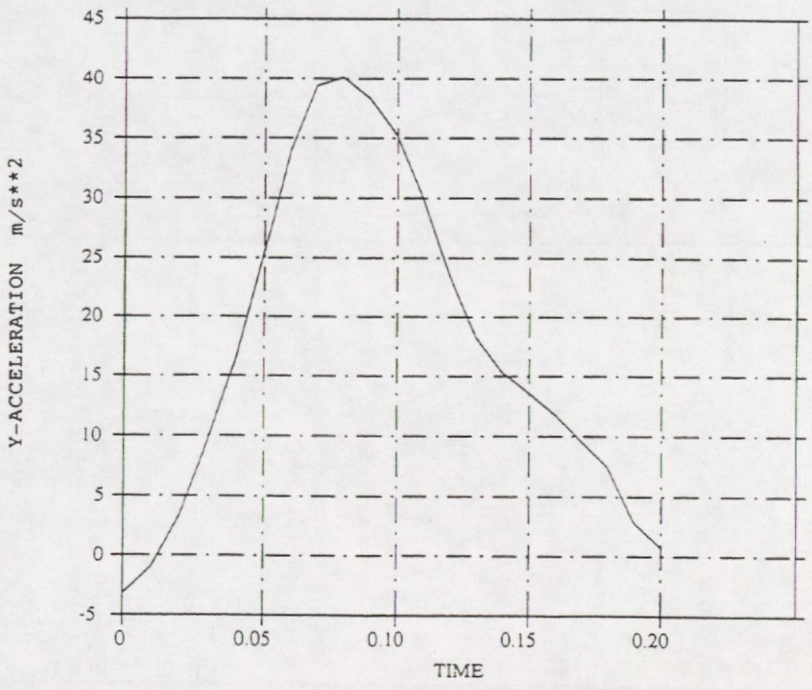
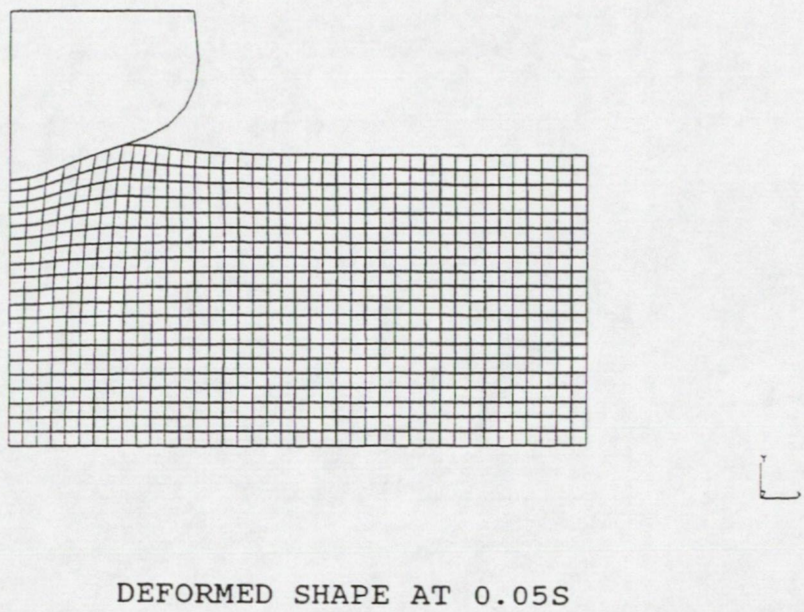


Figure 30 Deceleration-time history and deformed shape from analysis of Case 10 in MSC/DYNA



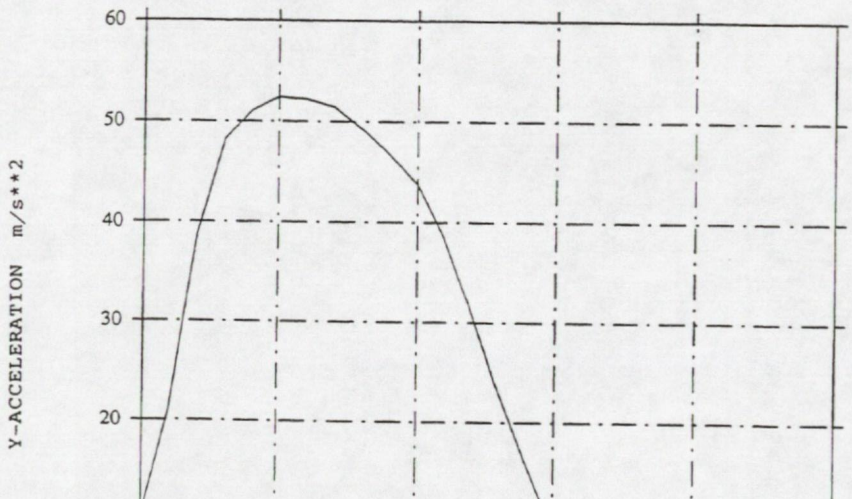
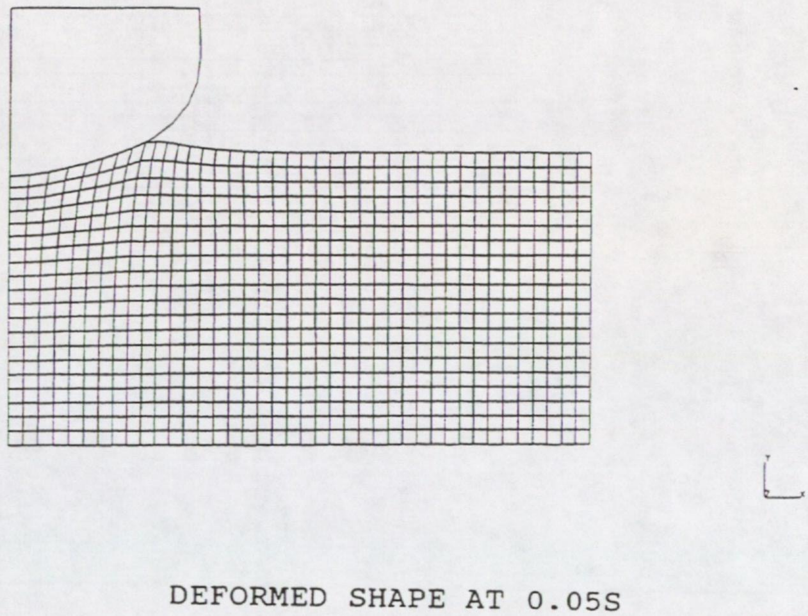


Figure 31 Deceleration-time history and deformed shape from analysis of Case 11 in MSC/DYNA



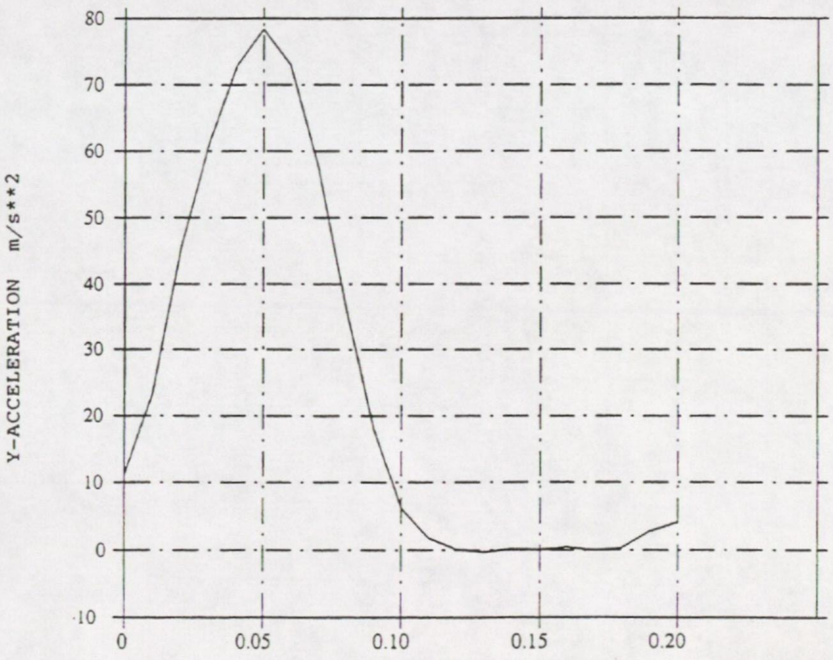
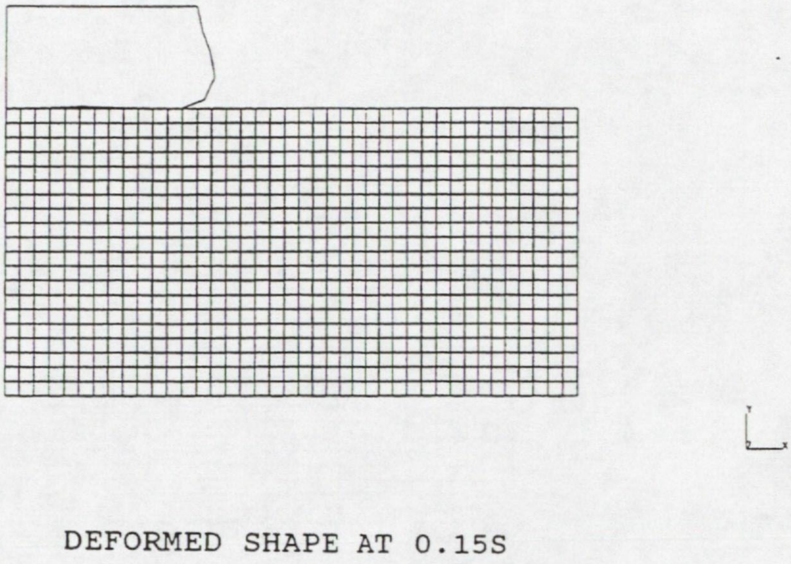


Figure 32 Deceleration-time history and deformed shape from analysis of Case 12 in MSC/DYNA



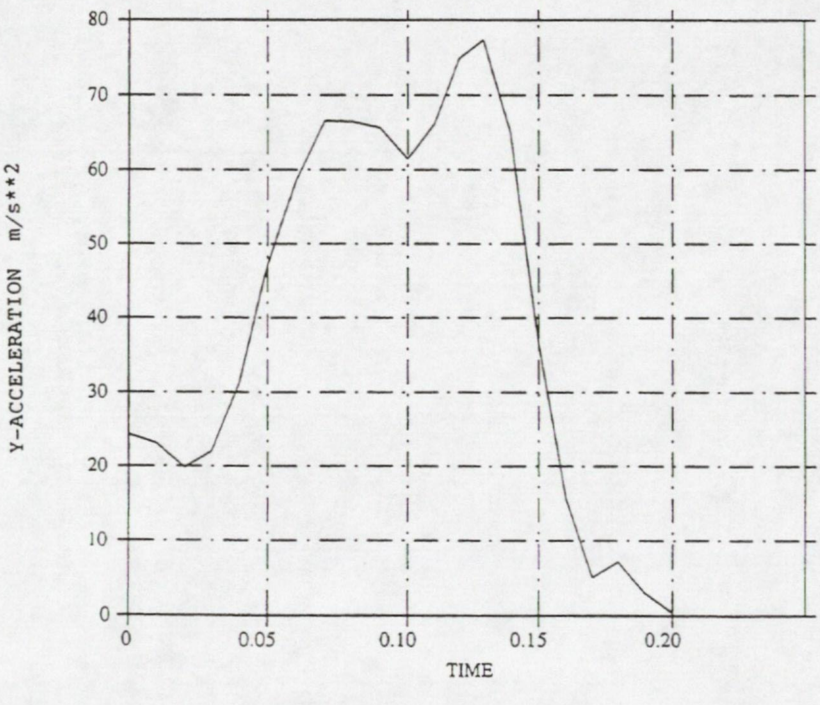


Figure 33 Deceleration-time history and deformed shape from analysis of Case 13 in MSC/DYNA

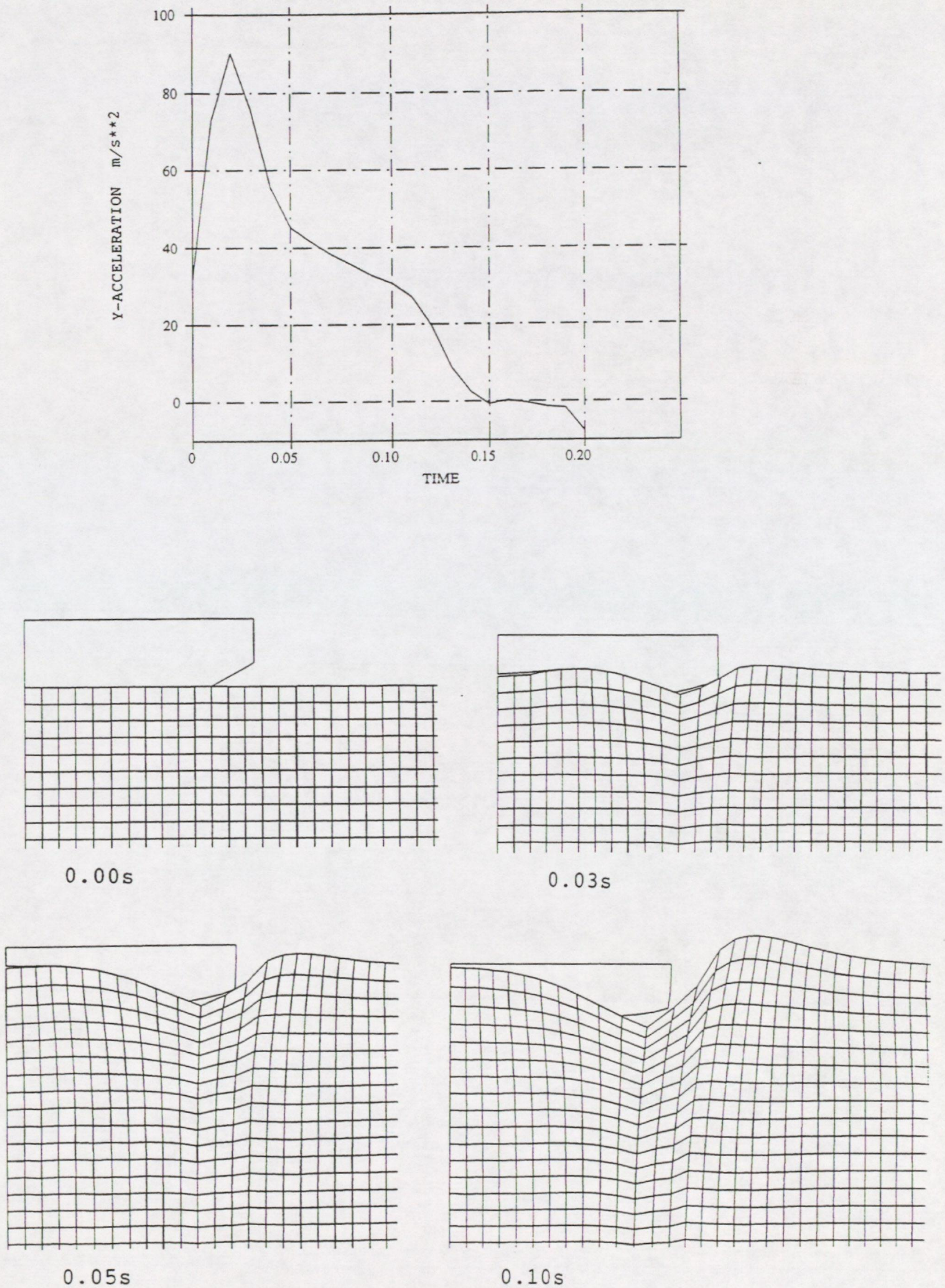


Figure 34 Deceleration-time history and sequence of structural deformations from analysis of Case 14 in MSC/DYNA

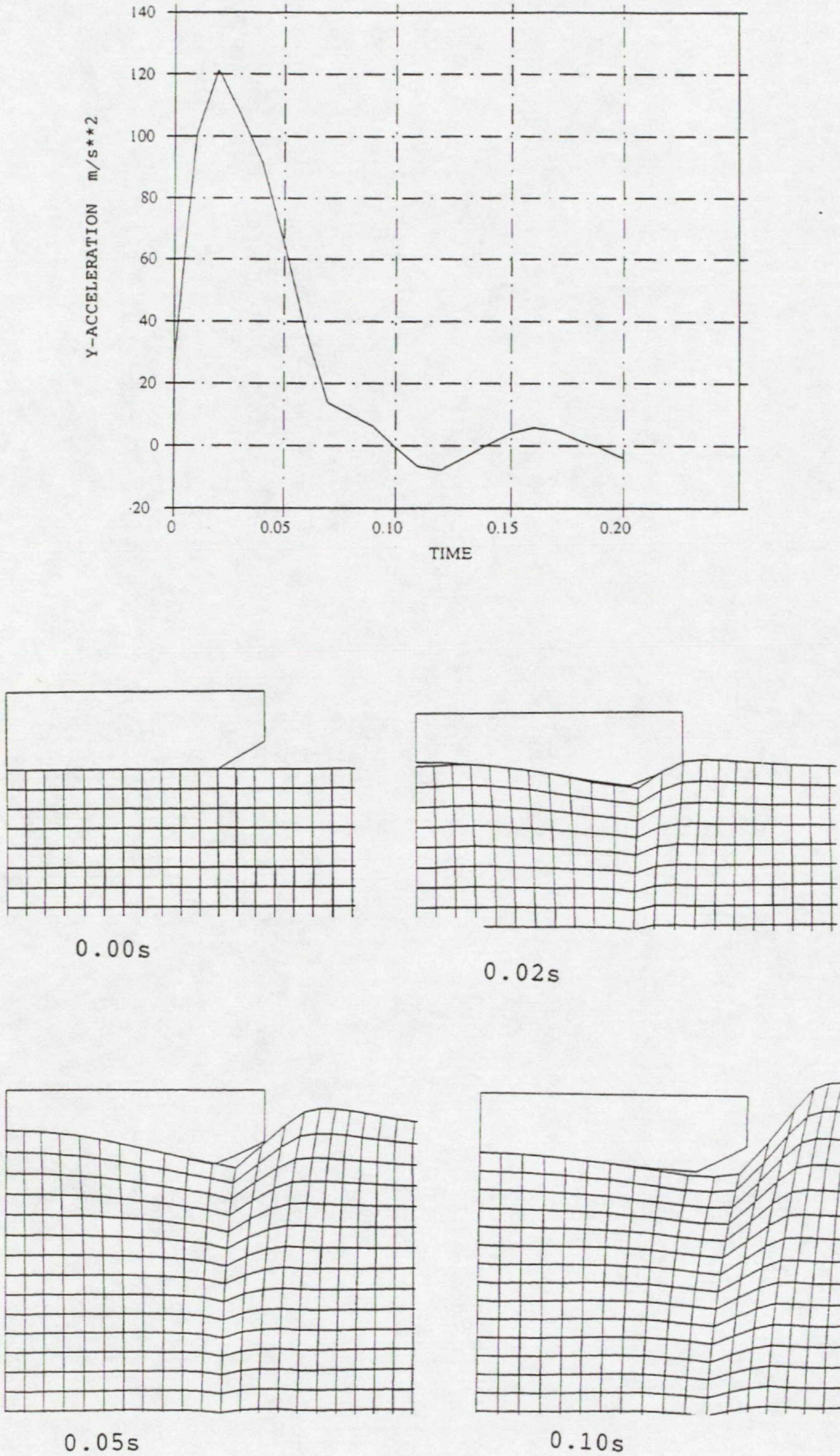
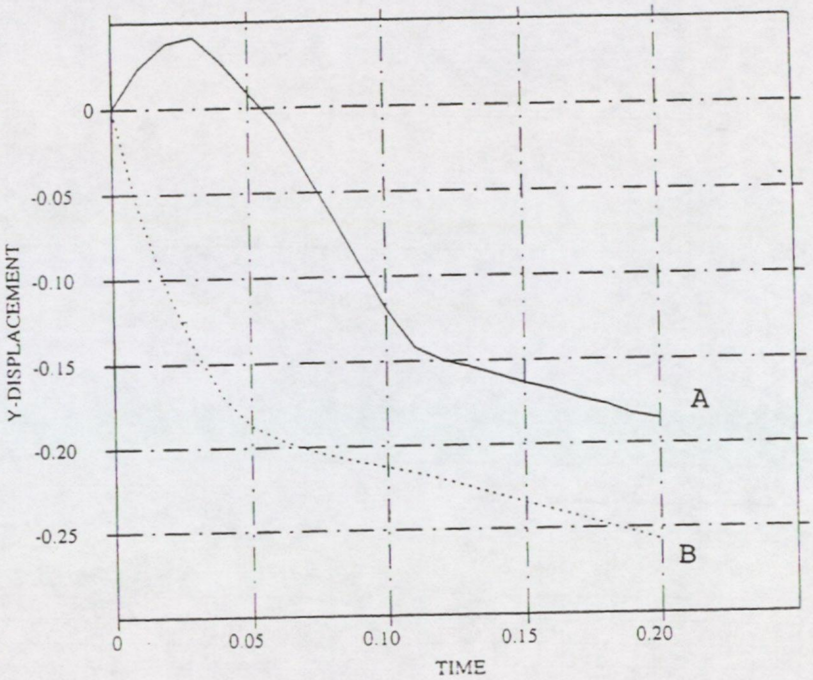


Figure 35 Deceleration-time history and sequence of structural deformations from analysis of Case 15 in MSC/DYNA



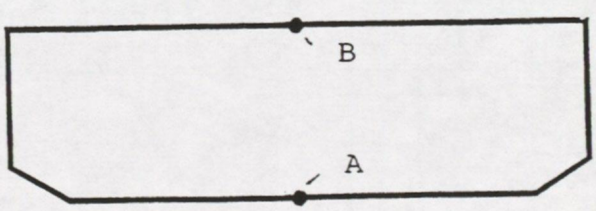


Figure 36 Deformation of floor from analysis of Case 15 in MSC/DYNA

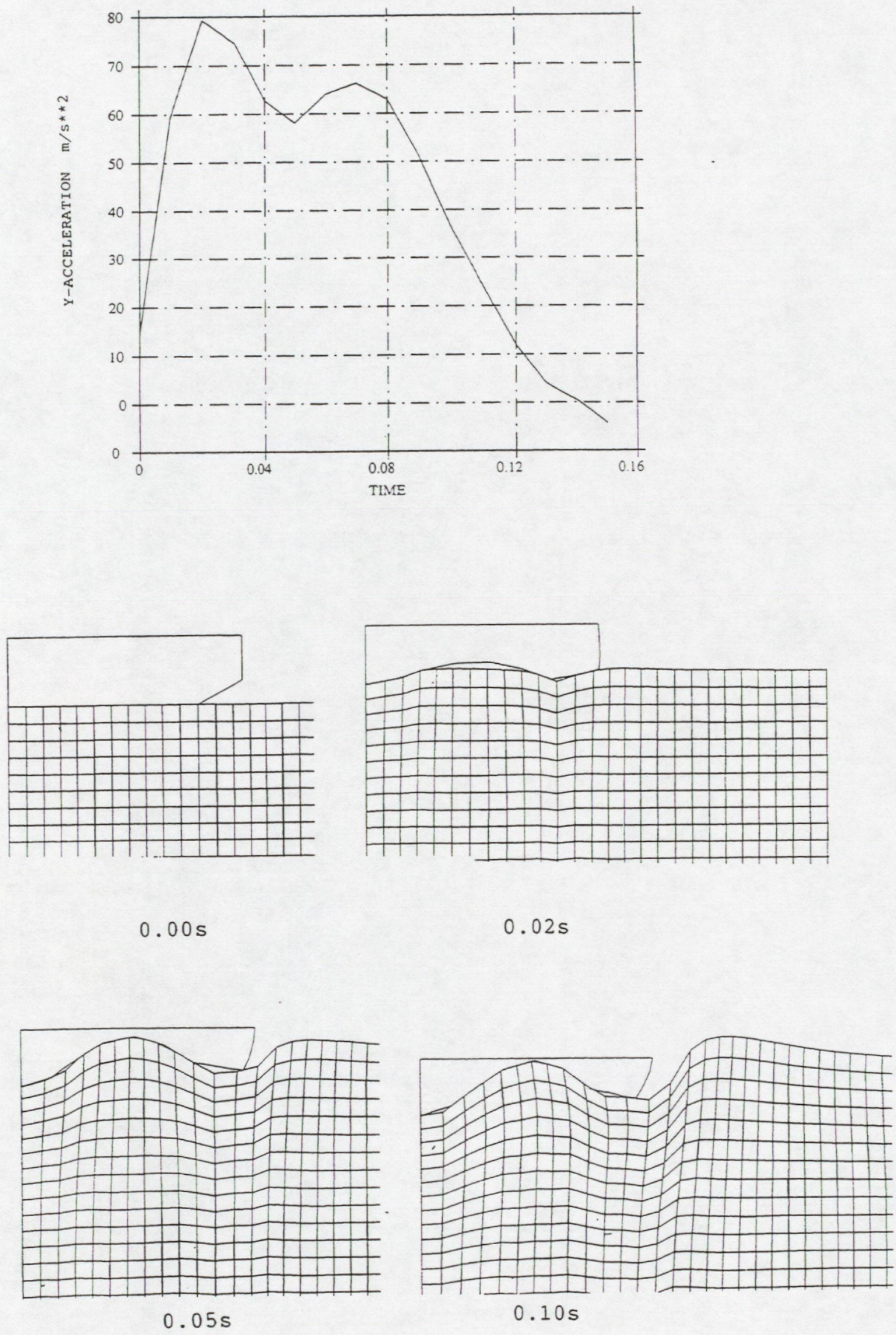


Figure 37 Deceleration-time history and sequence of structural deformations from analysis of Case 16 in MSC/DYNA

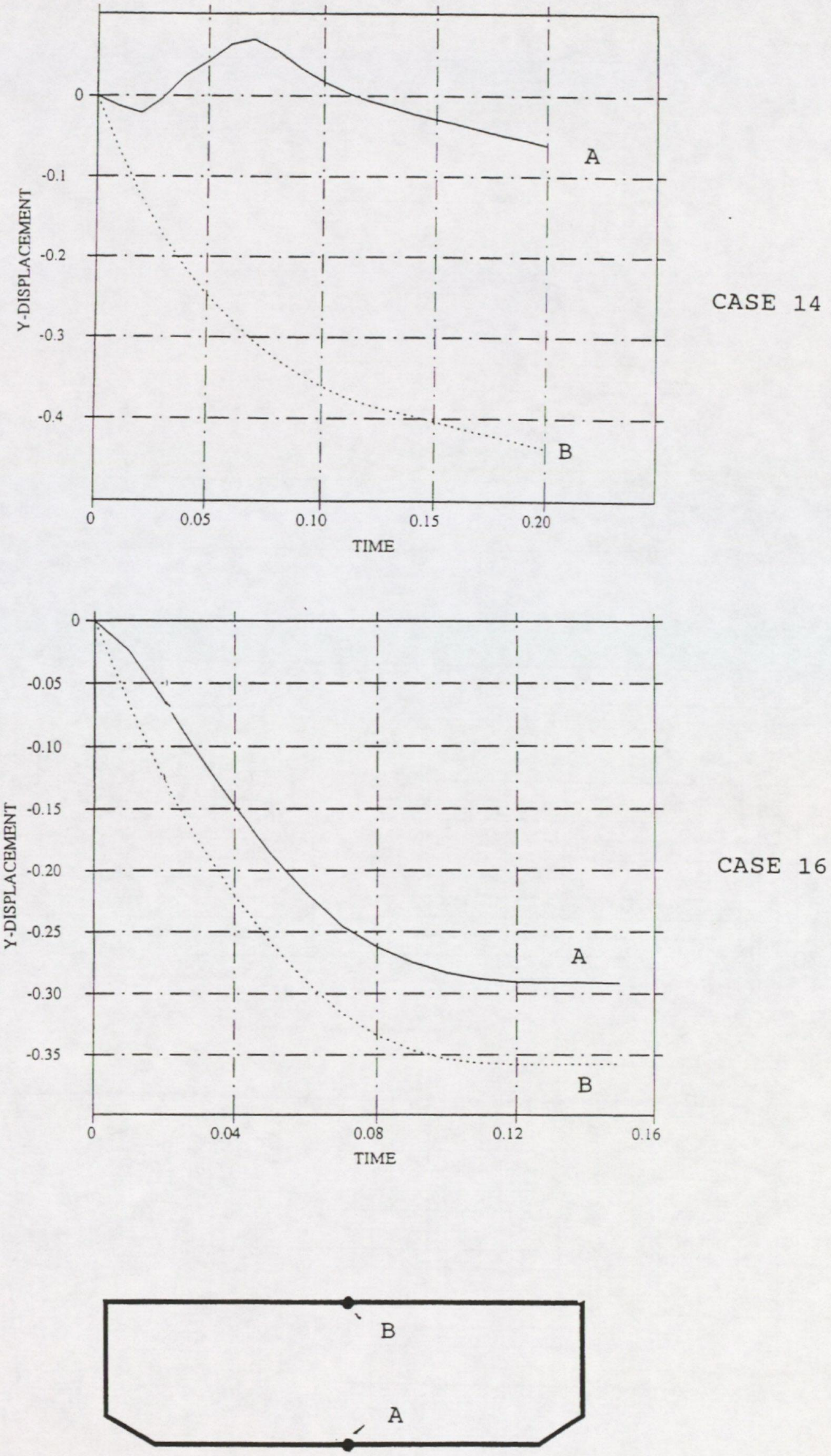


Figure 38 Floor deformations for Cases 14 and 16 from MSC/DYNA analyses

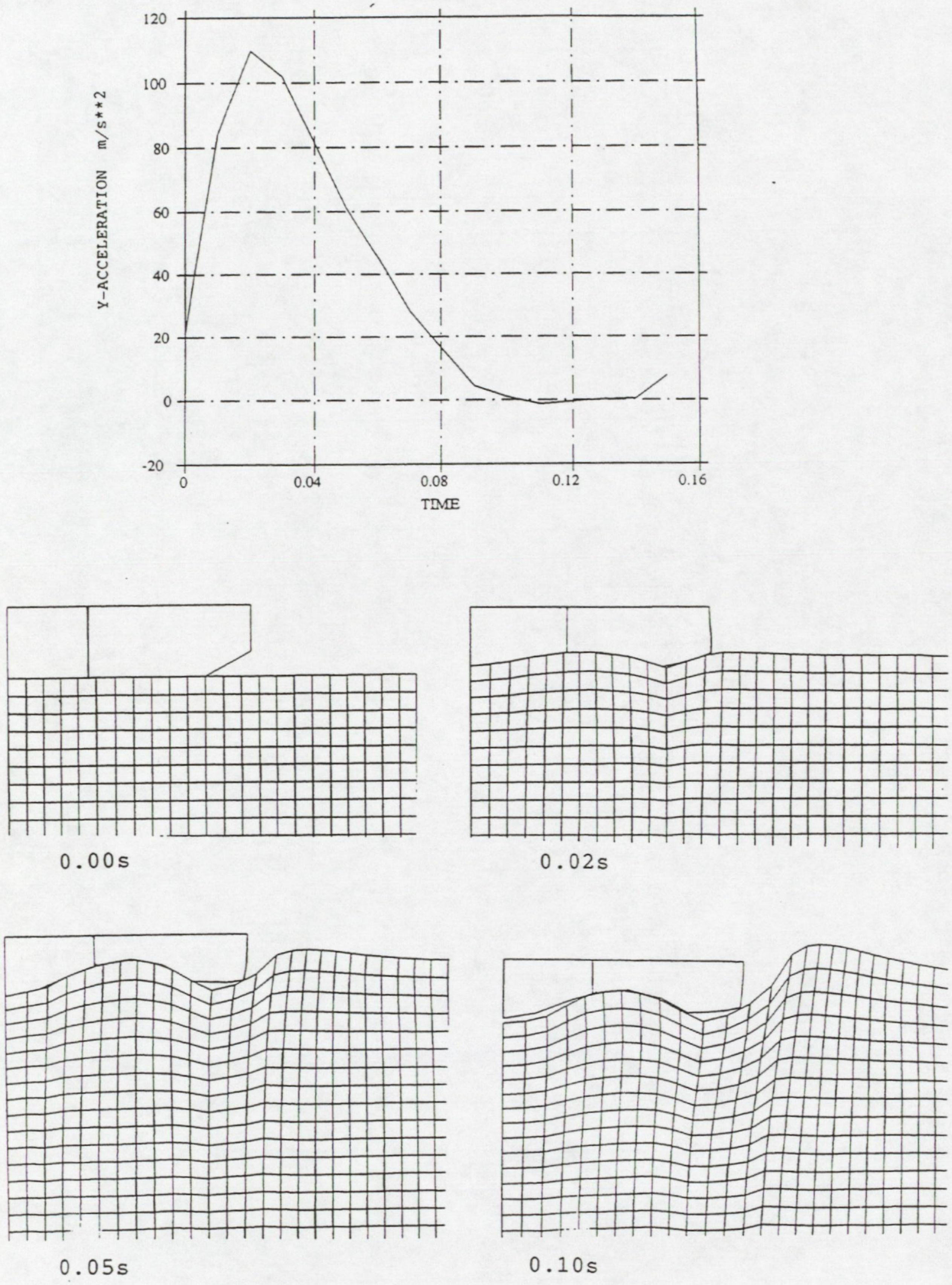
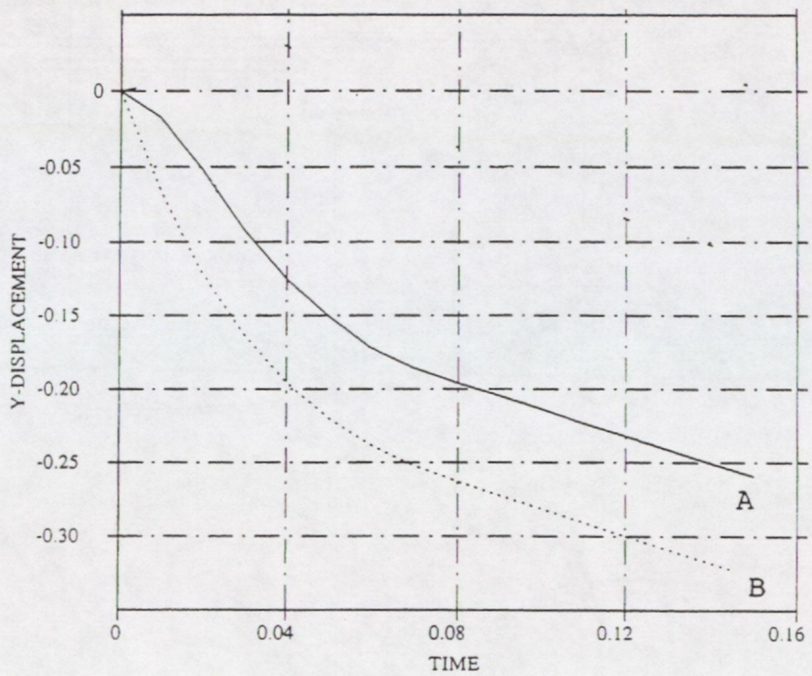


Figure 39 Deceleration-time history and deformed shape from analysis of Case 17 in MSC/DYNA



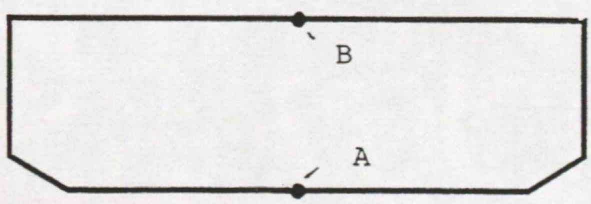
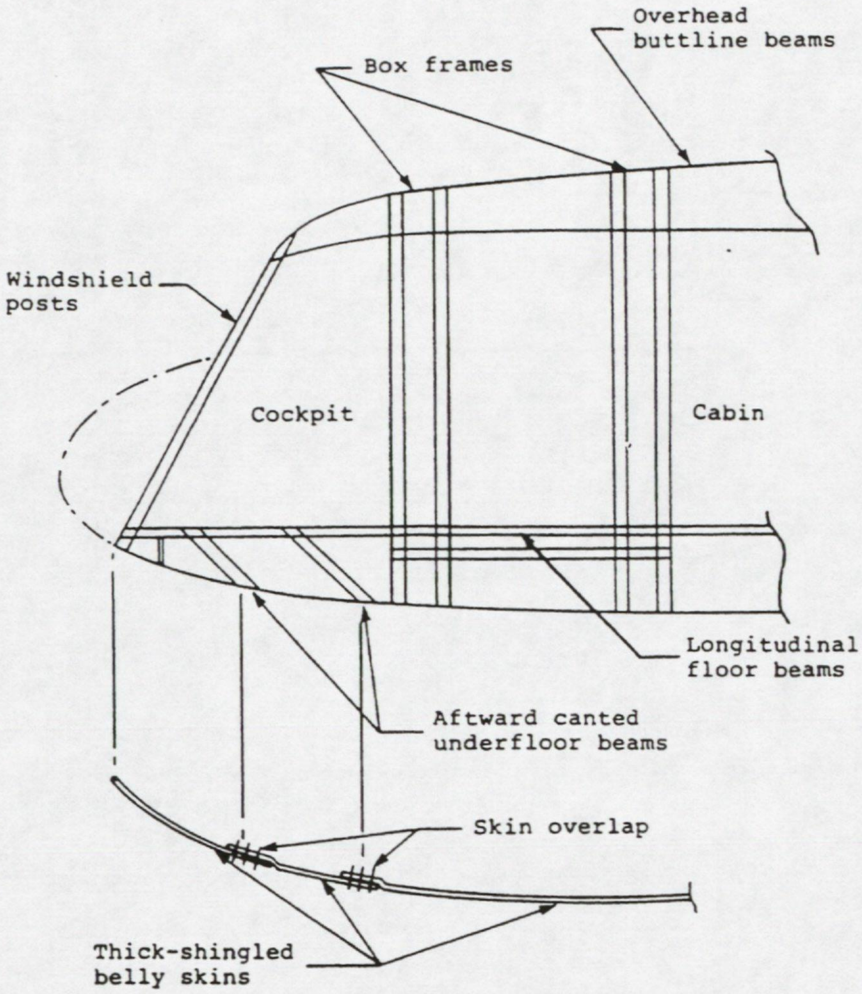
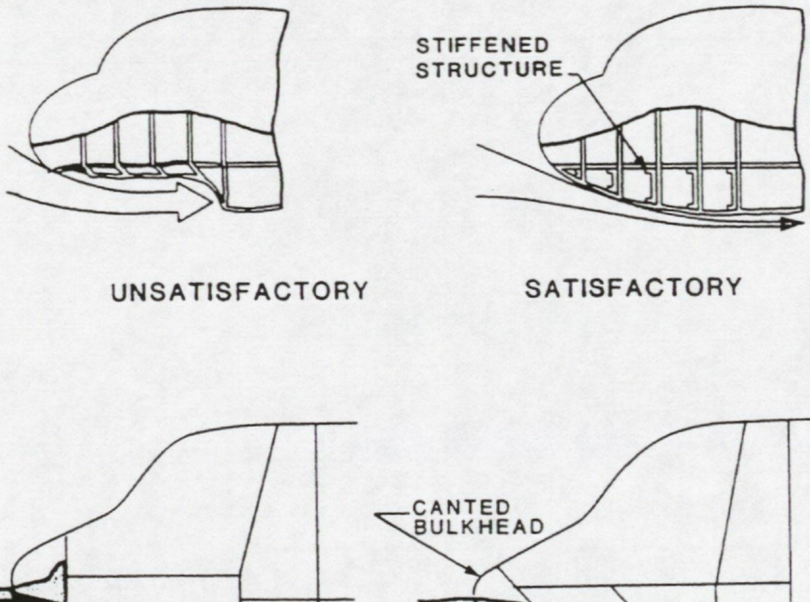


Figure 40 Floor deformations from analysis of Case 17 in MSC/DYNA





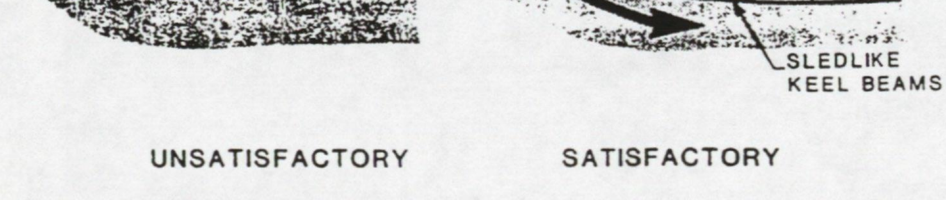
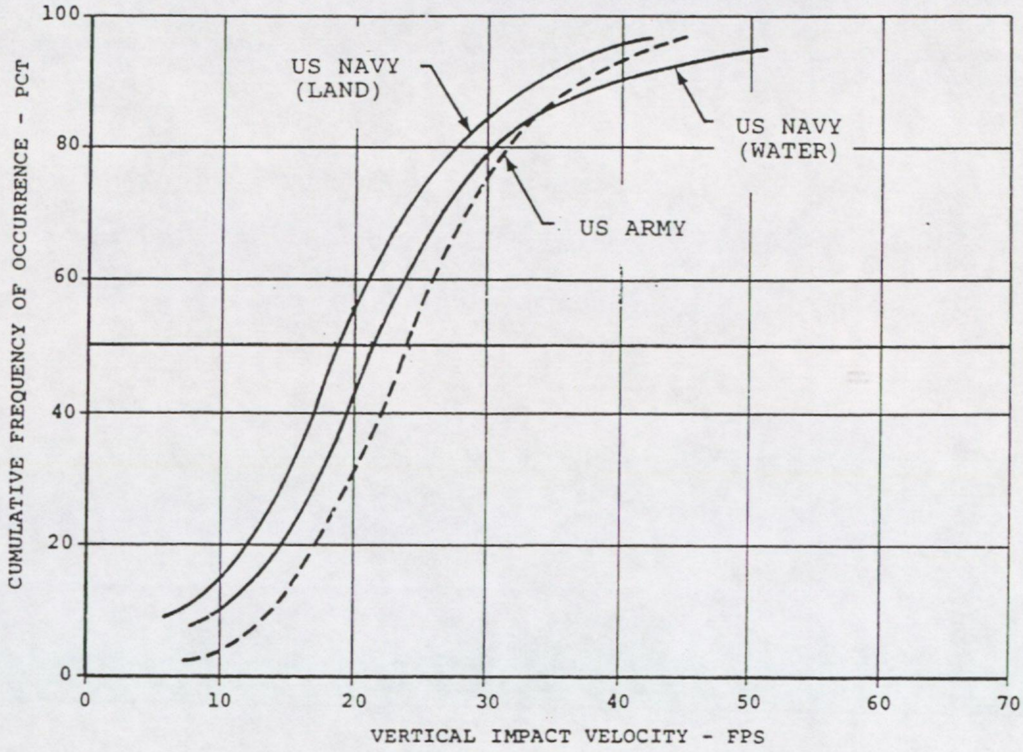


Figure 41 Structural configurations to improve the ability of helicopters to withstand longitudinal water impacts (from Ref. 1)



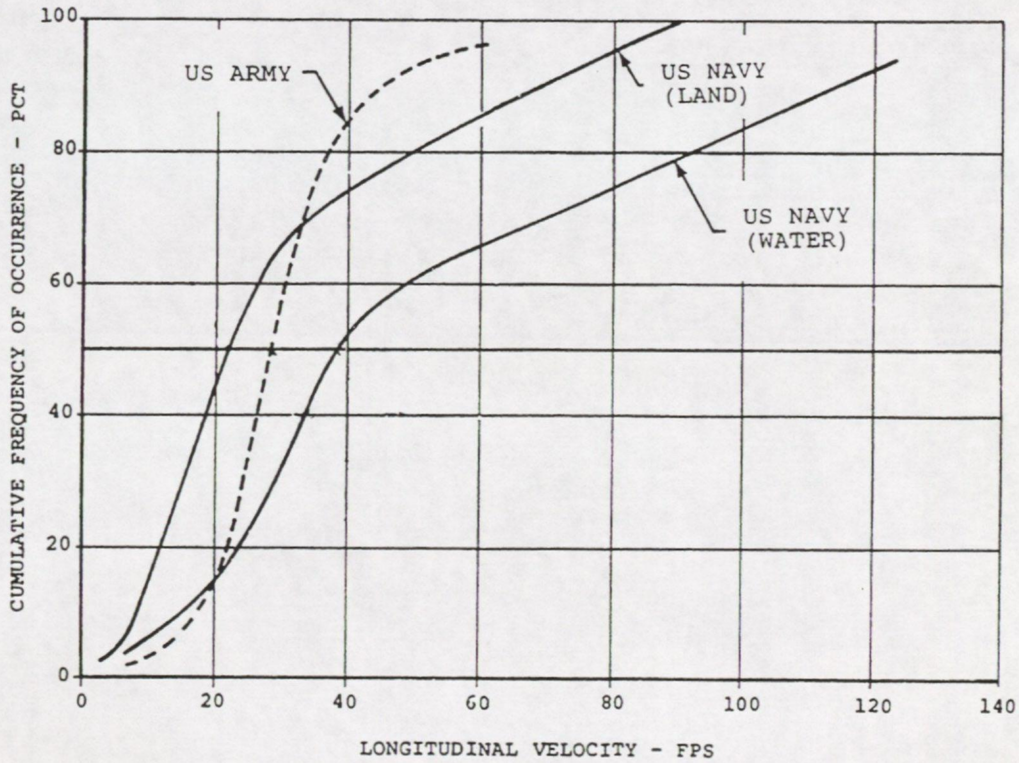


Figure 42 Cumulative frequency curves for vertical and longitudinal impact velocities for survivable US Army and Navy helicopter accidents (from Ref. 6)