The influence of energy attenuating aircraft seats on lumbar spine burst fractures: an incident reconstruction

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Abstract: Many injuries from helicopter crashes are due to large vertical loads transferred from the ground, through the aircraft and to the spine of seated occupants. Helicopter manufacturers aim to reduce these loadings through energy-attenuating seats. This report details the methodology used to reconstruct an incident and determine the loads experienced by the passengers, specifically a passenger who sat in the rear right seat of the helicopter and suffered a lumbar burst fracture. (a) analysing the injury; (b) analysing damage to the seat to estimate impact forces, and (c) analysing the mechanism of failure of the landing strut to calculate the impact angle and validate the impact forces at the seat. Once the range of force experienced by the passenger was estimated, the effect of the choice of seat was investigated to determine if this injury could have been avoided using seats commercially available at the time of helicopter manufacturing.

Keywords: helicopter; incident reconstruction; seat deformation; helicopter seat choice; crash safety; failure analysis; injury analysis; Euler buckling; materials science.

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1 Introduction

Occupant survivability during helicopter crashes has been a subject of aviation research and development since the 1960s (Smith and McDermott, 1968; Underhill and McCullough, 1972; Singley, 1973). This research has led to advancements in impact energy reduction technology. However, such technology is rarely adopted instantaneously, despite its ability to protect occupants from life-altering injuries. This paper aims to demonstrate how reconstruction methodology can be used to estimate the load applied to the occupant and therefore assess seat technology performance. To do so, a real-life case has been anonymised and will be used to show the application of such a reconstruction methodology.

As will be shown, information about the injury was used in conjunction with injury research and calculations based on the damage to the aircraft in order to make conclusions. This together with impact mitigation research allowed for a greater understanding of the circumstances of the crash and, therefore, provides insight into the usefulness of impact energy attenuation technologies.

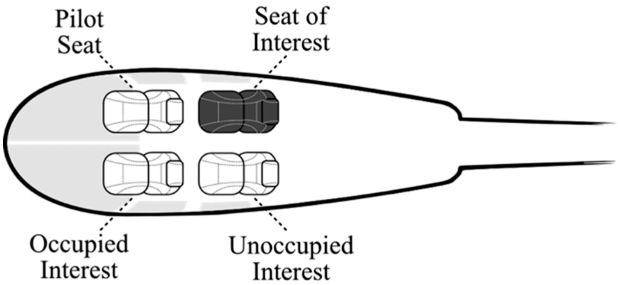
2 Case presentation

2.1 Incident

According to case materials, the incident involved a four-seat light helicopter on an environmental assignment carrying three adult men: a pilot and two passengers. While attempting to turn 180-degrees, the helicopter slowed to a hover and started descending to land before a gust of wind pushed the helicopter towards a nearby slope. The helicopter went into a fast vertical descent before its right side crashed into the slope with the aircraft remaining approximately upright. After the initial impact, the body of the helicopter rolled down the slope, on its left side. The aircraft eventually came to a stop in an inverted position on its left-side roof.

Injuries to the occupants ranged from minor to fatal. The current investigation focuses on one surviving occupant who suffered a lumbar burst fracture as a result of the crash. As shown in Figure 1, this occupant was seated in the back row on the right side. More specifically, focus was placed on the potential risk mitigation that could have been granted by energy absorbing seats, which were commercially available at the time of manufacturing but not installed in this particular helicopter.

Figure 1 Seating arrangement of the aircraft



2.2 *Injury analysis*

As a result of the impact, the rear-right passenger suffered an L3 ASIA (American Spinal Injury Association) Level C burst fracture in his lumbar spine. ASIA Level C corresponds to an 'incomplete' spinal cord injury meaning some muscle activity below the injured site remained (Kirshblum et al., 2011).

Burst fractures are characterised by a comminuted vertebral body fracture coupled with disruptions of both the anterior and posterior walls (Keene et al., 1989). Burst fractures occur quickly after loading (<25 ms) and tend to congregate between the L1 and L4 vertebrae during impact velocities common in helicopter crashes (Stemper et al., 2012). Sir Frank Holdsworth initially described burst fractures as resulting from direct axial impact loading to the vertebral body or in other words whole-body vertical deceleration. Another study looking at burst fractures due to axial compressive loading accounted for transmittance through the spine by measuring load at the bottom of the human cadaveric spinal segment. This research group determined that the average load to cause burst fractures was approximately 6.4 kN and ranged from 5.2 to 8.9 kN (Oxland, 1992). It is important to note that all peak loads, coinciding with the time of fracture, occurred in less than 25 ms. This is consistent with the timing of the injury cited above. More specifically, this research group also examined the relationship between cadaver specimen age and its fracture tolerance. This allowed fracture tolerance to be estimated at approximately 7.5 kN using data matching the injured parties demographic. Based on the accuracy of the test methodology and age-related data it was estimated that the passenger's L3 vertebral segment was exposed to at least 7.5 kN at the time burst fracture occurred. It is reasonable to assume that this represents a lower bound since the load has only been deemed necessary to cause the fracture and does not determine the total force present at the time of injury.

3 Methodology

To understand the dynamics of the crash, two main analyses were performed. These analyses focused on the energy attenuating seat and modes of strut failure. Through this information, a magnitude and direction of force sustained by both the occupants and helicopter were extrapolated. This information then allowed for a quantification and comparison of the response using different energy attenuating seat technologies.

4 Seat analysis

4.1 Descriptive analysis

The seats used in the case aircraft were energy attenuating seats, which are designed to deform upon impact, therefore reducing peak deceleration to the occupant. These seats involved an aluminium 'box' under the seat pan, which crushes and folds under load.

An examination of the rear right seat, after the incident, revealed that the seat experienced vertical buckling, as indicated by folding of the box panels along the front and inside walls of the seat (Figure 2). Additionally, vertical buckling of the rear box panel and the oblique orientation of the inside box panel (approximately 30 degrees from horizontal) indicates a posterior displacement of the top edge of the front panel. The greatest downward displacement was seen at the right rear corner, with apparent 'bottoming out' as compared to the downward displacement of the left rear corner or front panel.

Figure 2 Rear right seat comparison from undamaged to post-incident (damaged) (see online version for colours)

The front left and front right seats were also analysed in the same fashion. The vertical deformation showed agreement with the right rear seat but showed additional horizontal buckling.

Considering the deformation sustained with each seat, it can be reasoned that at initial impact there was a large vertical component directed downwards and a horizontal component that ran from the initial point of contact at the right rear skid tube (strut) and through the cabin, fore the centre of mass (CoM) causing an axial rotation of the fuselage to the left. The inertial properties of the human mass sitting in each seat would then push to the right causing the midline shift of the seat-buckling pattern.

4.2 Seat deformation analysis method

Knowing the overall dynamics of the seat deformation, it is then possible to link the forces involved to the injuries sustained. To do so, the deformation in the seats was measured using iSense 3D scanner (iSense 3D Scanner, 3D Systems corp., Rockhill, SC, 30 FPS). The files have a maximum volume of 3 m^3 and a minimum resolution of 1 mm. For each seat, a 3D object file was created and compared to the scan of an undamaged seat. The damaged and undamaged model were then entered into a modelling engine (MeshLab v1.3.3, ISTI – CNR, Piza, Italy) and overlaid (Cignoni et al., 2008). MeshLab is an open source tool developed for the processing and editing of unstructured 3D triangular meshes.

To overlay the seat models a coarse and fine adjustment process was applied. In the coarse adjustment, the bottom surface and front left corner of the damaged and undamaged models were visually aligned. Following the coarse adjustments, fine adjustments to the alignment were applied using the Iterative Closest Point (ICP) algorithm as described by Rusinkiewicz and Levoy (2001) to ensure that the orientation of the bottom front surface and bottom front left corner matched between damaged and undamaged models to within 0.1 mm error. Through this method, the change in position of the vertical walls, relative to the bottom front left corner could be estimated.

To determine the change in position of the vertical walls, 3D coordinates were recorded along the edges of all available walls of the undamaged seat model. The corresponding coordinates of the damaged model were recorded in the same 3D space. A vector of the displacement of each was then calculated for each pair of corresponding points. These vectors were used to calculate the displacement of each available edge and the resultant change in position using Matlab (Matlab 2013b, MathWorks, Inc., Natick, MA).

This resultant change in position of the vertical walls indicates the primary direction of the seat's deformation. Therefore, it can be used as an indicator of the principal direction of force (PDOF).

However, this estimate assumes the reference frame to be rigid. As described, any changes in position of the vertical walls are identified relative to the bottom front corner; however, any forces applied to the bottom of the seat during the incident may also influence the primary direction of the force that was applied to the seat.

After determining that the PDOF was in-fact vertical, the loading of the seat and spine was compared to research on technology with similar dimensions and materials (Nicholson et al., 1999).

5 Crosstube failure analysis

To validate the load bounds described above, it is relevant to examine the forces required to fracture the crosstube of the landing strut seen in Figure 3. When the helicopter first impacted the ground, the force of the impact on the strut travelled through different sections of the helicopter until it reached the passenger of interest. Therefore crosstube failure analysis allowed for validation of forces applied at the seat.

Figure 3 Crosstube break off point (see online version for colours)

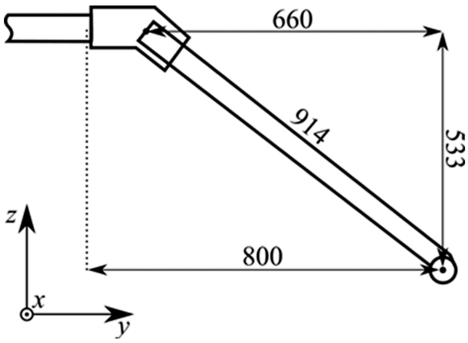
From the image available, it is known that the landing strut failed in bending due to tension at the top of the tube and compression at the bottom. Coupled with information about the location of said crosstube, it is possible to calculate force vector magnitude and impact angle the moment the helicopter struck the ground.

This crosstube was located just aft of the cabin and on the right side. Information gathered about the case helicopter revealed that this part was made of 7075-T6 drawn aluminium tubes, which have an ultimate tensile strength of 531 MPa. Symbols used in failure calculations are listed in Table 1 and dimensions of assembly are shown in Figure 4.

Table 1 Symbols used in calculations

Symbol	*Definition*	*Unit*
σ_{UTS}	Ultimate tensile strength	MPa
M	Moment about the neutral axis	Nm
y	Perpendicular distance to neutral axis	mm
I	Second moment of area about the neutral axis	mm
OD	Outer diameter of crosstube	mm
ID	Inner diameter of crosstube	mm
F_{impact}	Force of impact	N
F_y	Horizontal component of impact force	N
F_z	Vertical component of impact force	N
L_y	Horizontal distance from location of impact to crosstube	m
L_z	Vertical distance from location of impact to crosstube	m
L_h	Horizontal distance from impact location to strut assay	m
θ	Angle of impact with respect to horizontal	deg

Figure 4 Measurements of the rear right landing gear viewed from behind including coordinates system used in calculations (dimensions in mm)



The maximum bending stress a tube can withstand is defined by the following equation:

$$\sigma_{UTS} = \frac{M.y}{I} \tag{2}$$

Knowing the properties of the material and geometry of the part, it is possible to calculate each parameter and isolate for the moment M. Considering the thin-walled nature of the cross-section, the difference between yield strength and ultimate strength was reasoned to be negligible.

The second moment of area I is defined by the following equation:

$$I = \frac{\pi}{64} \cdot (OD^4 - ID^4)$$

$$I = \frac{\pi}{64} \cdot [(50.8 \text{ mm})^4 - (42.9 \text{ mm})^4] = 1.6 \times 10^{-7} \text{ m}^4$$

Considering the circular nature of the crosstube, this value is constant for tubes of this given thickness and does not change depending on the impact angle or the impact magnitude.

Lastly, it can be reasoned that the distance to the application of the moment is on the outside edge of the tube. This suggests that all values are known and the moment can be calculated. To do so, the following equation can be solved for the maximum allowable bending moment before failure of the tube:

$$M = \frac{\sigma_{UTS} \cdot I}{y} = \frac{531 \text{ MPa} \cdot 1.6 \times 10^{-7} \text{ m}^4}{0.0254 \text{ m}} = 3366 \text{ Nm}$$

The impact to the crosstube can then be defined by the following equation:

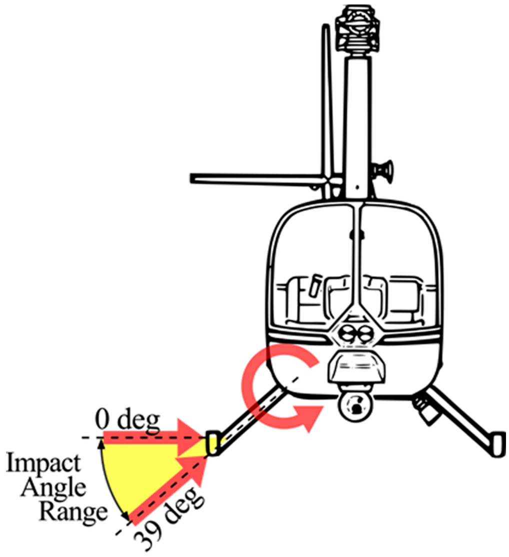
$$M = F_{\text{impact}} \cdot L_{\text{moment}}$$

Although, the magnitude of the force can be calculated, the angle of impact is still unknown and is key to validating the vertical force component transmitted to the seats and passengers.

Based on the failure mode described by the cross-section seen in Figure 3, it is also known that the strut failed in tension on the top portion and compression on the bottom.

This suggests that the crosstube was driven towards the midline of the aircraft. As shown in Figure 5, to generate such a moment, the angle of impact on the landing strut could not have reached more than 39° from horizontal. This angle represents the angle of the strut itself with the horizontal. A force at this exact angle would have resulted in a compression failure of the crosstube instead of the flexion failure observed. The horizontal angle, also denoted as 0°, is another limit of this range since past this angle, the vertical component to the passengers would have been in a direction opposite of what would cause a compression of the seats. Therefore, the 0 to 39° range of Figure 5 is the only range possible to generate the injuries seen in the passenger as well as the damage exhibited by the aircraft.

Figure 5 Range of impact angle to create the appropriate load (see online version for colours)



By expanding the moment equation further, it is possible to obtain a formula that allows for the angle of impact to be taken in to account as seen below.

$$M = (F_y \cdot L_z) - (F_z \cdot L_y)$$
$$F_y = F_{\text{impact}} \cdot \cos\theta$$
$$F_z = F_{\text{impact}} \cdot \sin\theta$$
$$M = (F_{\text{impact}} \cdot \cos\theta \cdot L_z) - (F_{\text{impact}} \cdot \sin\theta \cdot L_y)$$

6 Results

6.1 Seat deformation results

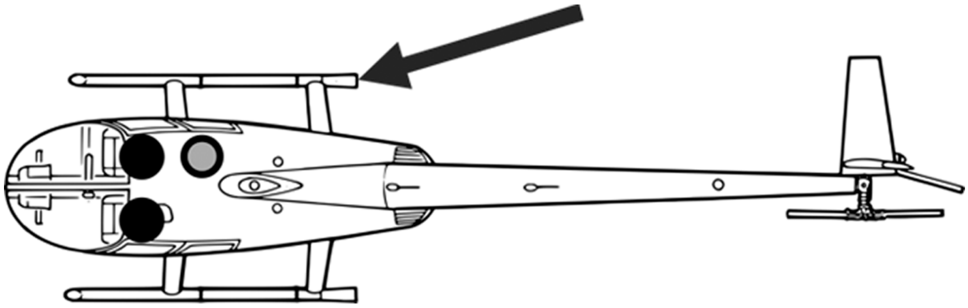
Based on the displacement measured at the edges of each seat, a force magnitude, and direction were estimated for each seat. The average displacement was measured along the edges of the available panels for each seat and can be seen in Table 2.

Table 2 Seat box panel edge displacement in mm

Seat	*Edge*	*Antero-posterior* (+*Anterior*)	*Superior-inferior* (+*Superior*)	*Medial-lateral* (+*Lateral*)
Rear right	Front	–130	–27	4
	Inside	–42	–225	40
Front right	Front	29	–135	–31
	Inside	–61	–95	–57
	Rear	42	13	–86
Front left	Front	–103	–25	137

As an indicator of the horizontal PDOF applied to each seat, the resultant direction of displacement was calculated given the measured displacement of the available edges. This resultant showed a leftward and anteriorly orientated force vector as illustrated by Figure 6.

Figure 6 Top view of force vector resultant and position of each occupant in aircraft



Vertical load from testing of box seating by Nicholson et al. (1999) found that partial buckling, 80 mm in the vertical direction, resulted in a maximum pelvic load of 6624 N. These tests used 0.64 mm thick aluminium sheet (2024-T3) walls in conjunction with corner stiffening angles to increase support. Further non-linear finite element simulations estimated buckling loads between 4223-8006 N for plates between 0.51 and 0.81 mm in thickness (Nicholson et al., 1999).

The seat examined by Nicholson et al. (1999) was described as 330 mm long by 273 mm high (width not given), while the case seat was 432 mm by 532 mm with a height between 335 mm and 456 mm. Therefore, with the case seat being marginally larger, the loading of the Nicholson seat of same material and aluminium thickness can be used as an approximate minimal loading for buckling. Comparison with testing from Nicholson et al. (1999) and knowledge of lumbar burst fractures suggests a range (lower and upper bound) of pelvic loading between 7500 to 8006 N.

6.2 Cross-tube failure results

Furthermore, using the equations previously developed for the crosstube impact, it is possible to estimate the angle at which the aircraft impacted. To do so, the crosstube failure load of 3366 Nm must be used in conjunction with the range of force necessary to produce a burst fracture, which was shown to be between 7500 N and 8006 N.

These loadings point to an impact of approximately 23°. This angle refers to the difference between the direction of the force vector applied to the crosstube and the horizontal plane of the aircraft. Considering that the crosstube is known to have impacted with a hill, a 23° collision appears reasonable and validates the bounds of loads estimated to be present.

7 Discussion

7.1 Multiple analyses in agreement

The incident reconstruction included multiple separate calculations, which independently aligned with each other thereby increasing the validity of the results. First, the lumbar spine tolerance to burst fractures for an appropriately aged male was found to be approximately 7500 N. Second, the load range to cause the buckling of the seats was calculated to be between 4223 to 8006 N. With the injury tolerance being within the buckling force range, it represents a lower bound of the force the passenger experienced based on his documented injury. Meanwhile, the seat compression load, namely 8006 N, represents the upper bound of the range of force applied to the passenger of interest.

Finally, this load range was applied to an analysis of the landing strut failure in order to seek agreement between the aircraft damage and injury to the occupant. This comparison showed that the loading to the passenger would have been possible with an impact angle of approximately 23° from horizontal. Given the evidence showing that the aircraft impacted on a hillside and falls within the narrow range of possible impact angles, the result provides additional credence to the global investigation.

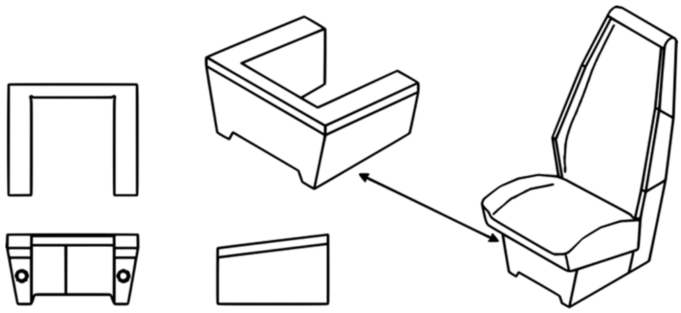
7.2 Effect of current seat technology

Based on the moderate to severe nature of lumbar burst fractures, it is relevant to consider whether this injury could have been significantly reduced or avoided completely. Using research and information about seats available at the time of helicopter manufacturing, it is possible to extrapolate the outcomes given different seat technologies.

First, testing results provided by the manufacturer of the incident helicopter included dynamic emergency landing testing, which illustrates the performance of the incident seats. These tests reported a lumbar load of 99% of the maximum allowable limit at 6626 N out of 6675 N when tested at an impact impulse with a peak of 30 G. According to burst fracture literature previously cited, this represents a probability of burst fracture of approximately 24–61% depending on which human cadaver dataset is used (Oxland, 1992). This data confirms that further improvement to the seat's energy absorption features may have been advisable. Additionally, Nicholson et al. (1999) pointed out in their research of this seat technology that using aluminium thicknesses of 0.81 mm, as with the case seat, can result in excessive stiffness and considerably greater lumbar loads than the maximum allowable.

However, research published in April 2002 showed a similar aluminium box seat technology tested to a 32.5 G peak deceleration impact pulse that produced better energy absorption properties (Nicholson and Turnour, 2002). Using a U-shaped box seat design from a GA8 aircraft (shown in Figure 7), lumbar loads were recorded at an effective load of 5790 N at 30 G (Advisory Circular 27-1B, 2008). Although similar in technology to the current seat used, if this seat design would have been used in the incident crash, the lumbar loads could have been reduced by 13%. In turn, this lowers the risk of burst fracture to between 13 and 57%. It is important to notice that the difference in seat attenuation has an even greater effect on the range of burst fracture probabilities.

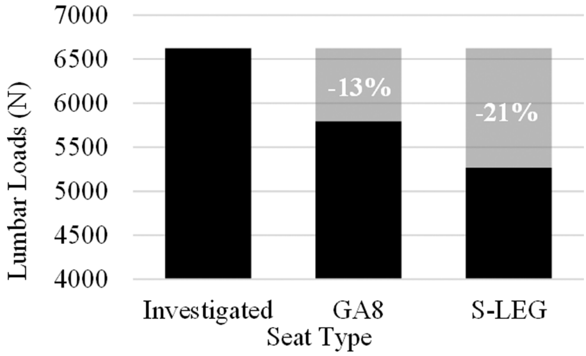
Figure 7 GA8 seat base



Another seat technology was also available at the time, as shown in a 1997 publication by Lankarani and Ng (1997). In another 32 G vertical impact test, a seat equipped with deformable S-shaped legs, made from aluminium 2024-T351, as shown in Figure 8, displayed energy-absorbing properties beyond that of both the incident seat and the U-shaped aluminium box of the GA8 aircraft. The lumbar load registered on a 50th percentile anthropomorphic test dummy (ATD) was 5614 N. To compare this value to the 30 G pulse used to test the other two seats, a correction factor can be applied using the method proposed in AC27-1B (Circular, 1999). This correction further reduced the load to 5262 N. As shown in Figure 9, the additional attenuation, when compared with the incident seat is 21%.

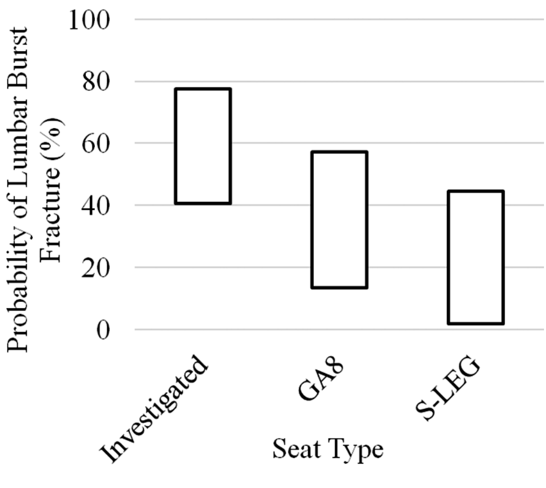
Figure 8 Energy absorbing seat with S-shape legs

Figure 9 Energy absorbing seat comparison



It is possible to obtain injury probabilities using this seat performance data together with the burst fracture tolerance information previously reported herein. Injury probability analysis suggested that burst fracture risk to the passenger of interest would have decreased from 40–78% with the incident seat to 2–45% with the S-shape design. Effectively, this difference suggest a risk of injury that is 'more probable than not' with the incident seat and an injury that is 'less than likely' with the alternative but available seat design (see Figure 10).

Figure 10 Probability of lumbar region burst fracture using each seat (lower to upper bound)



8 Conclusion

The burst fracture that the investigated occupant sustained during this incident likely occurred at initial impact as the aircraft made contact with the slope at an angle of approximately 23°. The lower and upper bound of the forces present at the subjects lumbar region during the incident were calculated to range from 7500 to 8006 N respectively. The lower bound was formulated using the lumbar spine burst fracture peak load tolerance while the upper bound originated from independent seat modelling results**.** Further, a crosstube failure analysis validated the lower and upper bound load range and revealed the impact angle necessary to cause the burst fracture with simultaneous failure of the rear crosstube.

Energy absorbing seat designs have been studied and publicly available for decades. A design using similar materials would have been able to attenuate the impact force by an additional 21% when compared to the incident seat design and was publicly available in 1997, prior to the helicopters manufacturing. This assessment shows that the probability of the occupant suffering a burst fracture during the incident could have been reduced from more likely than not to less than likely had an S-Leg design of similar material been used.

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