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ASSESSMENT OF INJURY PROBABILITY IN AIRCRAFT PASSENGERS DURING EMERGENCY LANDING CONSIDERING VERTICAL AND LONGITUDINAL ACCELERATIONS

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Abstract. *Airliners have been incrementing their profit by maximizing aircraft passenger occupation. This is evident by the progressive decrease in the pitch (distance between seats) in commercial aircrafts during the last decades. This work analyses, using numerical methods, how the pitch value is reflected in the passenger safety, by using dynamic simulations of different configurations. A test dummy is simulated in seated position with fastened seatbelt. Another seat containing a plastic joint is used ahead of the dummy. The use of a seat structure able to deform plastically along with horizontal and vertical imposed accelerations brings the proposed analysis closer to the crash-landing condition than most previous studies. Head injuries were analyzed through HIC – Head Injury Criterion and AIS – Abbreviated Injury Scale criteria. Neck injuries were categorized in serious (AIS 3, 4, 5 or 6) and non-serious (AIS 0, 1 or 2) according to maximum loads. The results show that the life risk increases proportionally to the pitch, although exceptionally close seats can also represent life risk.*

Keywords: *Injury severity, passengers' safety, aircraft safety, seat pitch, dynamic simulations*

1. INTRODUCTION

Airplanes are one of the top safest ways to travel: the chance of dying on a single flight is one in 29.4 million. Nevertheless, some factors like the high operational speed has the potential to produce serious injuries and, in some cases, death. Even with the technological advance, the survival rates in deadly accidents is just 24% (Static Brain, 2017).

According to Lariviere (2012), on a hypothetical flight with one hundred passengers only one single seat would be the company's profit. To improve their profit, airliners need to accommodate more and more passengers into the aircraft: the percentage of occupancy went up from 72.3% in 2000 to 82.1% in 2011 and the tendency for this percentage is to grow even more (Salomão, 2016). Another way to get more people inside the same space is to reduce the space between them. Pitch reductions range from 2.5 to 12.5 cm between 1985 and 2014 (McGee, 2014). Pitch reduction has implications for passenger comfort and may also have implications for safety e.g. making it difficult to get out of the plane in case of an emergency or leading the passenger to collide with the seat right in the front.

This paper presents a study about how the distances between consecutive rows of seats (pitch) influences the likelihood of head and neck injuries in the event of an accident with high survival rate, such as emergency landings. A simplified model with seats and a dummy is created, tested with longitudinal and vertical accelerations given by the current standards for aircraft seats certification and solved using the finite element method. For injury evaluation purposes, the Abbreviated Injury Scale (AIS) is used.

2. LITERATURE REVIEW

In 1986, a new test standard for aircraft seats is released (FAA, 2015) demanding dynamic tests with 16 g, replacing the previous one which only required static tests with 9 g. As the average age of Brazilian airlines fleets is no more than 20 years (AirFleets, 2017), it is estimated that the majority of the airplanes in operation for passenger transportation today have the seats certified according to the most recent standard. Figure 1a and 1b shows the test standard procedure and Fig. 1c shows the acceleration profile that should be applied. In this work, only Test 1 will be performed, since it's the only that contains vertical acceleration.

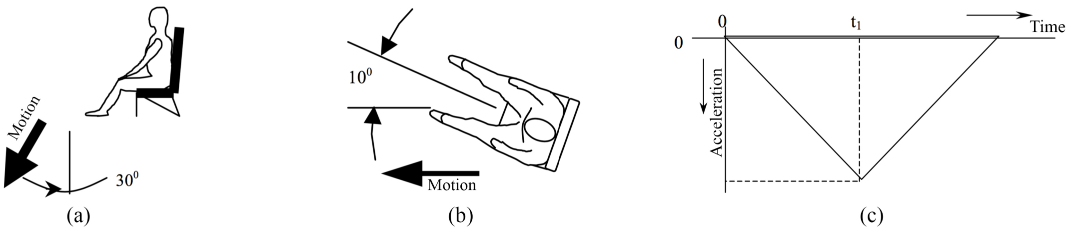


Figure 1. Standard tests for aircraft seats certification (a) Test 1, with vertical (normal) and longitudinal acceleration components, (b) Test 2 with lateral and longitudinal acceleration components and (c) ideal acceleration profile for both tests (adapted from FAA (2015)).

Mazzotti (2017) performed a similar test, with three different seat pitch distances, to find the likelihood of head and neck injuries but only considering longitudinal acceleration. Also, a rigid plate was used as the front seat not considering its share in absorbing the impact. The conclusion pointed to a decrease in life risk as the pitch grows.

It's very difficult to gather all head characteristics on a single injury criterion due to its complexity (Lima, 2009). The most used criterion is the Head Injury Criterion (HIC), which measures the likelihood of injuries resulting from linear accelerations to the head and to the brain:

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \left(\int_{t_1}^{t_2} a(t)dt \right) \right]^{2,5} \right\}_{max} \tag{1}$$

Where $a(t)$ is the acceleration, in m/s^2 , calculated at the head's center of mass and $(t_2 - t_1)$, in s, is the time lapse where the max HIC occurs. It could assume any value representing the time which the acceleration is acting on the head.

In order to classify and describe the severity of injuries, the Abbreviated Injury Scale (AIS) is widely used, according to Lima (2009). It's a code created by the Association for the Advancement of Automotive Medicine (AAAM) with seven numbers that tell the type, location and severity of an injury (Lesko *et al.*, 2010). Here, only the location (head) and the severity are used. Severity is given on a scale from 0 (no injury) up to 6 (maximum). Also, both scales are combined together in order to determine the likelihood of injury occurrence of each severity.

The neck injuries evaluated here refer to cervical spine injuries caused by axial tensile and compression loads, shear forces and bending moment (head rotating forward and backward). All such loads should be measured on the occipital condyle, upper neck region. There's only a roof limit for this loads which indicates an AIS 3 injury or higher if exceed (Lima, 2009). Those limits are listed on Tab. 1. From this point onward, neck injuries exceeding the limits (meaning AIS 3 or higher) are considered to be fatal.

Table 1. Neck injury limits by load type.

Load	**Limit**
Axial Load - Tension	3,30 kN
Axial Load - Compression	4,00 kN
Longitudinal Shear Force	3,10 kN
Longitudinal Bending Moment - Forward	190,00 Nm
Longitudinal Bending Moment - Backward	57,00 Nm

3. METHODOLOGY

3.1 Landing Conditions

An emergency landing condition will be used to perform the tests. Between 2007 and 2016, 48% of fatal accidents occurred at the final approach and at landing phases - which together represent only 4% of flight time (Boeing Commercial Airplanes, 2017).

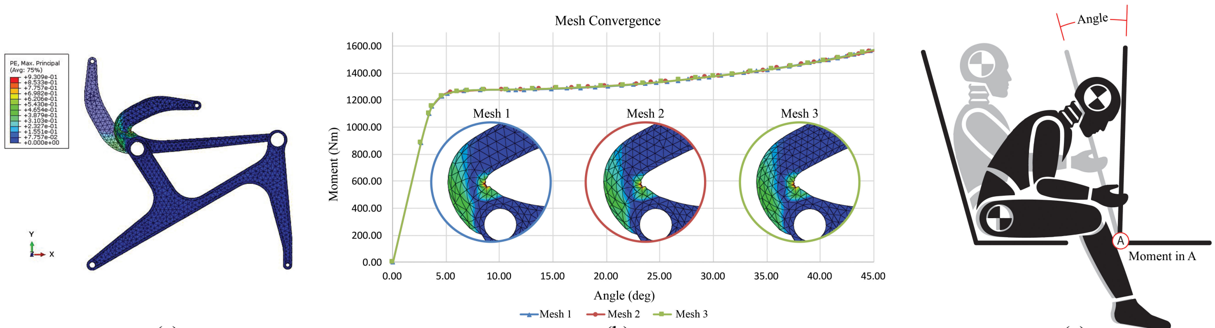
Test 1 from the standard procedure for certification of seats will be used with acceleration peaks shown in Tab. 2 for longitudinal and vertical components.

Table 2. Acceleration components.

Component	**Acceleration peak**
Longitudinal	7.00 m/s^2
Vertical	12.00 m/s^2

3.2 Seats and Seat Pitch

In order to bring the simulation closer to reality, it is assumed that, in the front seat, only the structure linking the seat and the backrest absorbs energy and this energy is absorbed through plastic strain. In order to consider large deformations that could lead to the formation of a plastic hinge in the structure, the model assumes that the material, aluminum 6061-T6 behaves as a bi-linear material and follows the model described by Su *et al.* (2016). The structure was based on a patent (Zimmermann *et al.*, 2013) and the model was solved with the finite element method Fig. 2a, which after a convergence analysis has provided the necessary data – a moment-versus-angle curve, as seen in Fig. 2b to insert the plastic hinge as a torsion spring into the main analysis at point "A" shown in Fig. 2c.



(a) (b) (c)

Figure 2. Seat structure (a) deformed and undeformed shape on top of each other, (b) mesh convergence with a moment-versus-angle curve and (c) draft showing the angle used and the point A, where the hinge is located.

It was assumed the backrest was a mixture of 35% polymers with density of 1000 kg/m^3 (Vilar, 1986) and 65% foam with density of 30 kg/m^3 (Foam Online, 2017). The average density was estimated at 370 kg/m^3. For comparison purposes, the same seat and pitch distances chosen by Mazzotti (2017) were used: seat dimensions were selected from Roskam (1986) as a simplified model; for pitch distances, a few more cases were evaluated ranging from 630 mm up to 750 mm with 20 mm steps. Also, the same dummy, which represents 50% of the male population, was used as it provides the necessary data to perform the study by default.

4. RESULTS AND DISCUSSION

4.1 Head Injury

The model is able to provide values for HIC according to Eq. (1). It has been observed that HIC increases with increasing pitch as can be seen in Fig. 3. The increase in HIC may be related to the time the head has to accelerate before hitting the backrest. The more time acceleration has to act on the head, the more velocity the head gets, boosting kinetic energy up. Therefore, the deceleration experienced by the head when hitting the front backrest is higher and the impact more severe. Such interpretation is consistent with Eq. (1), when $(t_2 - t_1)$ is small and $a(t)$ is large leads to highers HIC values. So, the emergency position (otherwise called brace position) might actually help in the severity of injuries, since the head is placed close to the front backrest. It is important to emphasize that this result contradicts some of the preliminary conclusions proposed by Mazzotti (2017), who found that HIC increases with decreasing pitch.

AIS analysis for the head also points on the same direction as likelihood of a severe injury increases with increasing pitch. As Figure 4 shows, even in the worst case, more than 90% of the injuries would be classified as AIS 2 or less, meaning up to moderate injuries.

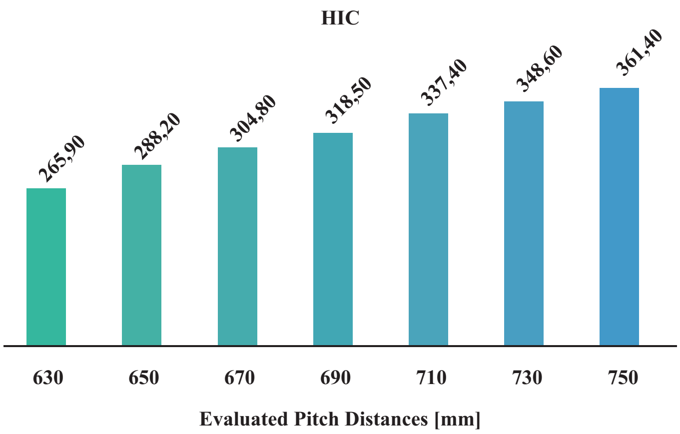


Figure 3. Results for HIC.

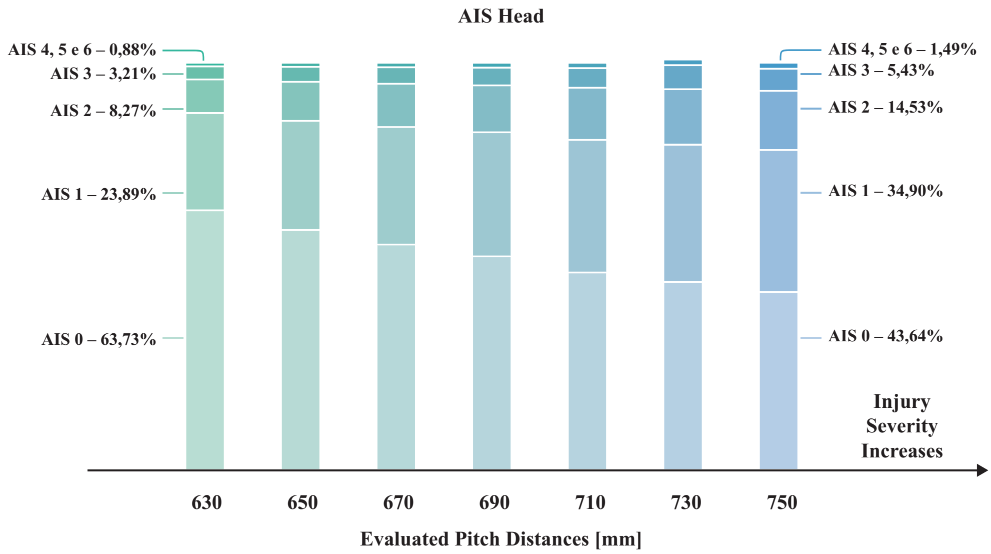


Figure 4. Results for AIS Head.

4.2 Neck Injury

The maximum neck shear forces decreased with increasing pitch and in all cases the limit (Tab. 1) was not reached, as Fig. 5 shows. The same happened with the forward bending moment (Fig. 6) while the opposite occurred with the backward bending moment (Fig. 7), where the four cases with higher pitch resulted in fatal injuries i.e. its maximum exceed the limit. Such behavior may be explained by the different angles between the head and the front backrest at different pitch distances. It is important to keep in mind that shear force peaks and forward bending moment peaks happened at the same time as the impact and backward bending moments happened shortly after. Also, both moments use the same axis, located between head and neck link, therefore keeping track of the forces generated by head movements with respect to the neck only.

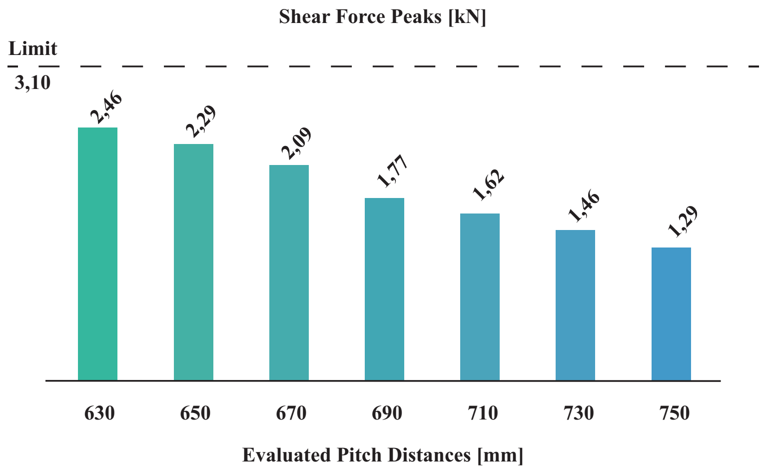


Figure 5. Maximum neck shear forces.

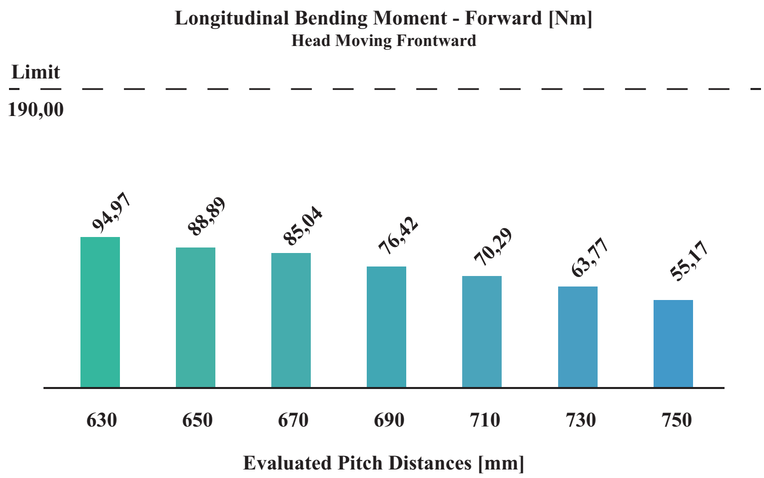


Figure 6. Maximum neck frontward bending moment.

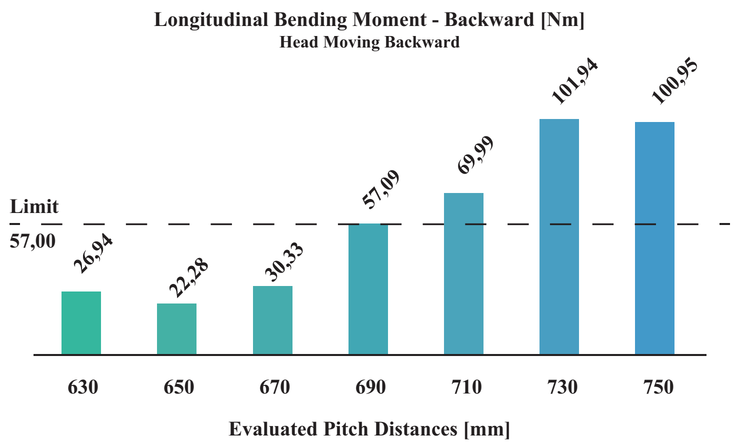


Figure 7. Maximum neck backward bending moment.

The compression load (axial) presented a tendency to increase slight with increasing pitch, as Fig. 8 and in the injuries would probably be non-fatal in all cases. The same didn't happened with the axial tensile load, where no tendency was observed and only the lower pitch case was fatal (Fig. 9). It is important to notice that the compression occurred are the time of the impact and the tension shortly after. A possible explanation for the compression load tendency may rely on the

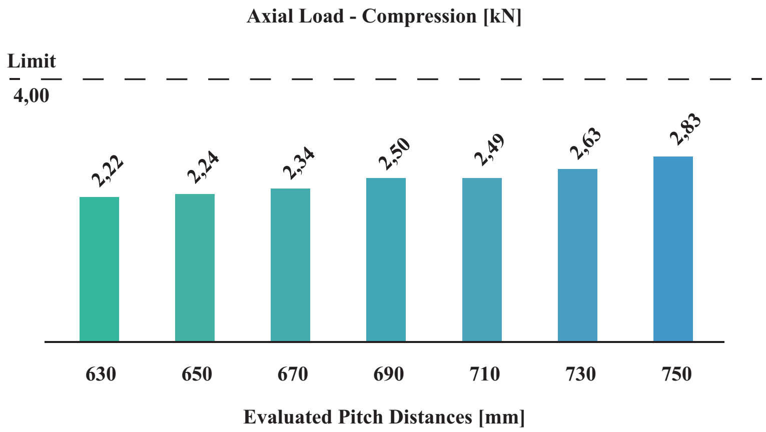


Figure 8. Maximum neck axial load (compression).

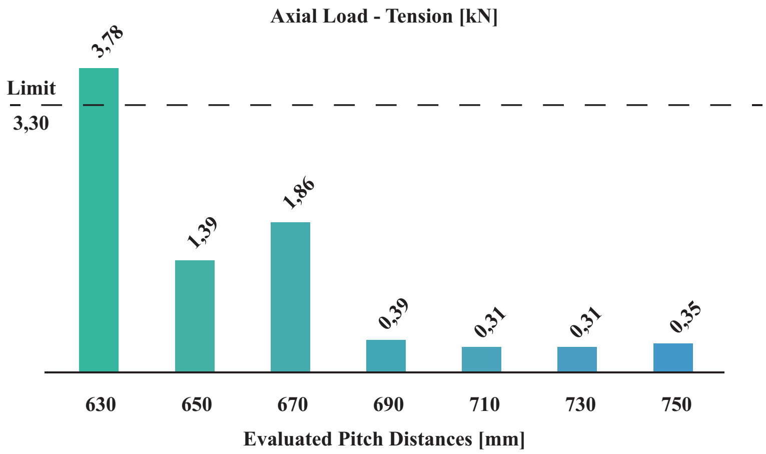


Figure 9. Maximum neck axial load (tension).

fact that the body tends to keep going forward due to its inertia, while the head had already hit the front backrest, which compresses the neck. The tension, on the other hand, has no tendency whatsoever, therefore further analysis is required in order to completely understand the phenomena.

Again, it is important to bear in mind that, like the backward bending moment peaks, the axial tensile load peaks occurred at an instant after the first impact, so it's not possible to state that those values do represent reality.

In future works, it might be addressed questions regarding impact safety positions as to its effectiveness protecting injuries or even the possible existence of a optimum pitch distance subject to safety aspects and comfort, along with airliners' profit. It's also possible to feed the model with more realistic data, like emergency landing real data instead of using standardized ones. Besides, a more realistic model for the seat could be used, given its importance evidenced in this work.

5. CONCLUSIONS

This paper shows that consideration of impact-absorbing effects on passenger-seat backrest as well as the addition of the vertical component of the acceleration generated results contrary to the preliminary studies (Mazzotti, 2017).

It should be noticed, however, that a dynamic analysis of seat structure is more appropriate to obtain the moment-versus-angle curve, since dynamic effects of plastification were disregarded in this work when performing a static analysis.

From results obtained here, it was observed that the life risk increases with increasing distance between consecutive seat rows (pitch) – although very close seats can also increase life risk. This conclusion was made possible through observation and analysis of Head Injury Criterion (HIC), used to measure the potential for head injuries, of Abbreviated Injury Scale (AIS) scale, used to quantify injury severity, and of forces and moments acting on the neck.

Another important aspect, regarding the methodology used, is the fact that the increase in complexity covers this work with more realism, when compared to the one performed by Mazzotti (2017). Furthermore, it suggests intuitively more logical conclusions as well. It is evident, therefore, that the behavior of the seat in front of the passenger directly influences the results.

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7. RESPONSIBILITY NOTICE

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