Computational Analysis of a Car Chassis Frame under a Frontal Collision

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Abstract -This paper aims at studying the frontal collision of a car frame using non-linear FEA (Finite Element Analysis). Three frontal crash situations are evaluated: a full frontal impact against a rigid barrier and two frontal impacts with 40% overlap against an ODB (Offset Deformable Barrier). These three simulations are intended to mimic the FMVSS no.208, the 96/79/EC and the EURONCAP tests. The model of the chassis used in the simulations – a Ford F150 - is based on one that has previously been published in another paper. However, in that paper, the simulation only considers a static load on the bumper (a pressure) and the conclusions do not reflect what would happen during a real impact with dynamic loads. Several results are presented and discussed: the dissipated energy during the impact, the acceleration time history and the HIC (Head Injury Criterion) are evaluated from the set of results so obtained. Furthermore, different test situations and initial conditions have been applied, aiming at better understanding the frame's response in a real impact situation.

Keywords: Crashworthiness, Computational simulation, Head Injury Criterion (HIC), Finite Element Analysis (FEA).

1. INTRODUCTION

During a crash, the car and its passengers withstand very high levels of acceleration (negative, in the sense of deceleration). The term crashworthiness expresses the ability of a vehicle's structure to protect its occupants in a serious real world crash [1]. In other words and in most cases, crashworthiness refers to the vehicle's structural ability to deform in a plastic manner (if it is a metallic material) or fracture and fragment (if it is a brittle plastic material) and yet provide adequate space for the occupants within it [2]. Examples of systems that are also used in motor vehicle safety include ABS, airbags, seatbelts, head restraints, anti-intrusion bars, collapsible steering columns, inner padding, laminated windshields, crumple zones, crush cans, etc [3]. The principle is that the energy dissipated during the impact is transmitted to the vehicle's, relieving its occupants from it.

At the advent of motoring there were no regulations or tests regarding the crashworthiness of vehicles. However over time regulations have been put in place and independent bodies now analyse the crashworthiness of vehicles [1, 2, 4, 5]. These regulations are constantly becoming stricter and more restrictive as to the performance of vehicles in crash situations. In response to the test becoming stricter cars have evolved and now they tend to be based around the concept of having a collapsible outer structure which will absorb energy at a constant rate, in essence dissipate the energy of the crash to protect the passenger [6]. The second part is the vehicle will have a very rigid structure around the passengers which will then transmit the forces around them rather than through them as well as preventing incursion of foreign bodies [7].

The aim of this paper is to analyse the sub frame of a Ford F150 pickup truck to see how it performs in high speed crash situations, while, at the same time, looking at the uses of impact testing using Finite Element Analysis (FEA) simulations. In particular, an improved simulation will be run in comparison to one previously published. This will allow better understanding the response of the car frame under frontal impact previously presented in [8], by including dynamic loads in opposition to static loads only.

2. THE HEAD INJURY CRITERION

The Head Injury Criterion (HIC) is an empiric quantification of the passenger's head damage risk during an impact [9]. Dummies that are used in crash tests have several accelerometers attached to the head area which record the deceleration during the impact time span. Because the head has mass, and recalling that Newton's second law of motion states that the force F is equal to the product between the mass m and acceleration a, $F = m \cdot a$, higher levels of acceleration will be matched by higher forces that the head, brain, neck and other vital organs will have to withstand. The HIC is defined as a function of the resultant translational acceleration and time as:

$$HIC = \max_{t_1 < t_2} \left[(t_2 - t_1) \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right)^n \right] \quad (1)$$

in which $n = 2.5$ for the head. This equation takes into account both duration and weighed value of the acceleration for the time interval $\Delta t = t_2 - t_1$. This time interval is determined for the maximum HIC obtained during the impact. It is assumed, however, that for $\Delta t > 36ms$ and for peak acceleration values that last less than $3ms$ the injury risk does not increase, i.e., there is no effect on the brain [9]. There are some questions that arise with respect to the HIC. As such, improved injury criteria has been proposed [10]. However, for the sake of this paper, since anthropomorphic test dummies are not considered and only the frame is being studied, the HIC seems a suitable candidate to quantify and compare the frame's performance under different scenarios.

3. NUMERICAL MODELS AND SIMULATIONS

The dimensions of the Ford F150 chassis frame were based on specifications found on the Ford website and the internet [8, 11]. For the 3D CAD model, four parts have been modeled and assembled together: a block mass, the simplified chassis frame, an ODB (Offset Deformable Barrier) and a rigid wall (figure 1). The block mass, ODB and rigid wall were modelled as solids, whereas the chassis frame, being a moderately thin structure, was modeled with shell elements in the Finite Element Model (FEM) package ANSYS. A detail of the mesh can be seen in figure 2.

The chassis frame is made from steel square and rectangular tubes. Three chassis frame thicknesses have been considered: 1/8" (3.18mm), 3/16" (4.76mm) and 1/4" (6.35mm), as in [8], although according to US specifications instead. The block mass at the back exists to simulate the whole mass of the vehicle which, for an unladen Ford F150, is 1600 kg approximately.

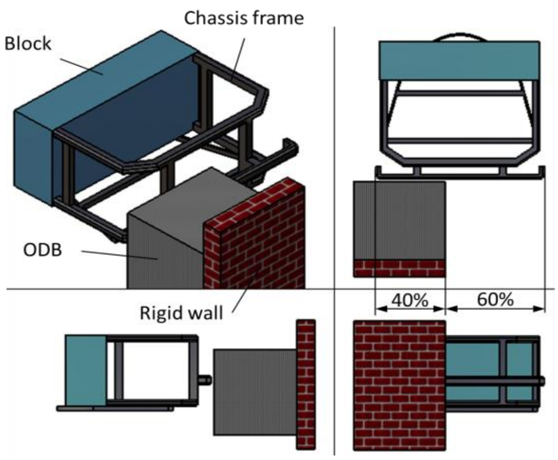

Fig. 1 CAD model for a 40% offset impact.

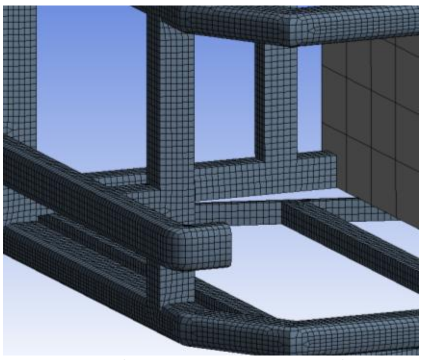

Fig. 2 Detail of the mesh on the chassis frame.

The Chassis frame material model selected was Nonlinear Structural Steel (bilinear isotropic to allow for plastic deformation) with density 7800 kg/m3, Young's modulus 200 GPa, Poisson's ratio 0.3 and yield strength 250 Mpa. The block was modelled as a rigid body. However, its density was adjusted to 2309 kg/m3 to reflect the total mass of an unladen vehicle.

Three frontal crash simulations were evaluated in order to mimic three test protocols: the FMVSS no. 208 [1], the 96/79/EC [4] and the EURONACP [5].

The FMVSS no. 208 (Federal Motor Vehicle Safety Standard) vehicle-into-barrier test [1] is a full frontal impact (100% obstruction at the front of the vehicle) with initial velocity set at 30 mph (48 km/h or 13.4 m/s) against a rigid anchored wall. Some simulations have also been run at lower speeds to show the evolution of the HIC with increasing speed.

Both the European Frontal Impact directive 96/79/EC [4] and the EURONCAP [5] testing protocols are crash tests in which there is a 40% overlap of the obstacle with the vehicle's front, as illustrated in figure 1. However, the initial impact velocity is set at two different values: 35mph (56 km/h or 15.6 m/s) and 40mph (64 km/h or 17.8 m/s), respectively. In both these protocols the crash barrier is an ODB, contrary to the FMVSS no. 208. It is made from the build-up of Al honeycomb layers. To model this barrier accurately in a FEM software is a quite complex task. Thus, for the sake of computational efficiency, the average density and strength have been extracted from the data from the EURONCAP protocol [5] and applied into a single solid block, using the same reasoning as the one used when applying the principle of homogenization in the modelling of composite materials [12]. Some of the material properties were also taken from [13]. CAD models were obtained in CATIA V5, pre-processing was done in ANSYS Workbench, the solution was obtained using the LS-Dyna solver under ANSYS Mechanical APDL and post-processing of the results was done with LS-PrePost.

4. RESULTS

4.1. ASSESSMENT OF THE QUALITY OF THE RESULTS

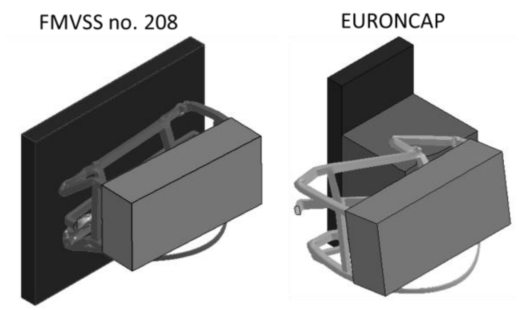

Fig. 3 Sample images of the crashes for a 1/8'' wall thickness frame.

Figure 3 shows two sample images of the crash for a 1/8" wall thickness frame in the FMVSS and EURONCAP simulations. Firstly, from figure 3, it is visible that the impact is progressing as is expected during an impact situation. The mesh has not split or produced any sharp edges which would suggest low quality of mesh and as a result invalid simulation results. Also it is visible from these crash scenarios that the sub frame has performed much alike the actual sub frame in a Ford F150 during crash testing [14], even if there is no engine, wheels and many other components in the simulation that have important effects on the way the vehicle deforms and decelerates.

4.2. Analysis of the influence of different thicknesses in the three test protocols

Different frame thicknesses have been compared: 1/8'', 3/16'' and 1/4''. Plots of the acceleration vs time results during the impact for the three test protocols are presented in figure 4. The corresponding HICs are plotted in the bar chart figure 5.

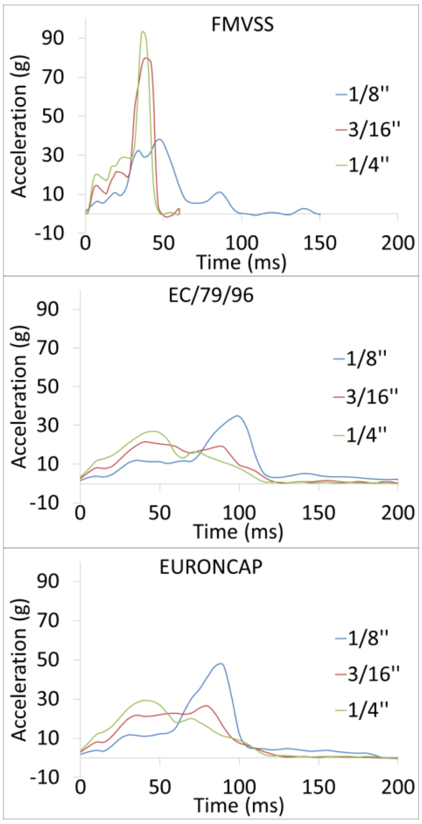

Fig. 4 Plots of the acceleration vs time during the impact for three different thicknesses on the three test protocols.

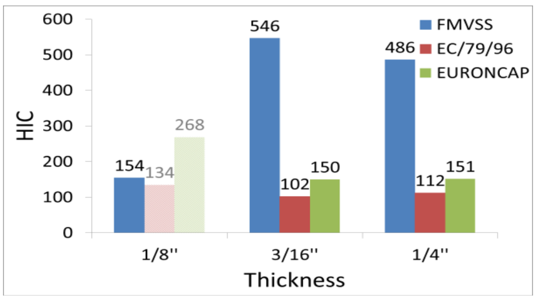

Fig. 5 HIC for three different thicknesses on the three test protocols (96/79/EC and EURONCAP results for the 1/8'' were deliberately "greyed out", as explained in the main text).

Results for the FMVSS test protocol (against a rigid barrier with 100% overlap) are in accordance to what would be expected initially: the larger the thickness of the frame, the highest the acceleration peak and the shorter the impact duration. However, for the other test protocols it is the 1/8'' frame thickness the one that is producing larger levels of acceleration. The reason for this second peak that is dominating the results is because the frame is "too soft" and it deforms until the rigid mass at the back also hits the ODB (figure 3 on the right). Although this could represent the effect of the engine and other components (up to a certain extent), the comparison does not make sense anymore, because it is the front structure alone that is being analysed and compared. Thus, these results have been greyed out from figure 5.

Regarding the evolution of the HIC, one interesting aspect to point out is that a lower value was obtained for the 1/4" frame when compared to the 3/16" on the FMVSS test (figure 4). The reason for this is because during the first 25 ms (approximately) the 1/4" is decelerating more quickly than the 3/16". Then, there is the peak, which, although higher, is narrower for the 1/4". Since the HIC is defined as a function of the resultant translational acceleration over time, it is not suprising that under certain circumstances the HIC may be slightly smaller for stiffer structures.

4.3. Comparison between the three test protocols

The three test protocols were compared in terms of the maximum acceleration and HIC. A single thickness of 3/16'' was considered in this comparison. Plots of the acceleration *vs* time for these three simulations are presented in figure 6. Some relevant results are presented in table 1 as well, in which the kinetic energy before and after the impact,

E_1 and E_2, the percentage energy dissipated, E_d and the maximum acceleration, a_{max} are included.

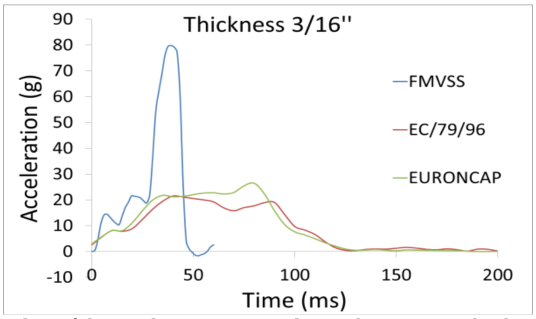

Fig. 6 Plots of the acceleration vs time during the impact in the three test protocols for a 3/16'' wall thickness frame.

Table 1 Impact results for the three test protocols for a 3/16'' wall thickness frame.

Test	E_1 (J)	E_2 (J)	E_d (%)	HIC	a_{max} (g)
FMVSS	1.48 x10^5	1.30 x10^3	99.1	486	79.8
96/79/EC	2.01 x10^5	5.61 x10^3	97.2	102	21.5
EURONCAP	2.63 x10^5	1.02 x10^3	99.6	150	26.4

As expected, the impact against the rigid wall with 100% overlap (FMVSS) is the one presenting the highest HIC, almost 5 times larger than the one from the 96/79/EC test and 4 times larger than the one from the EURONCAP test. However, the impacts on the 96/79/EC and EURONCAP tests are for speeds 15% and 33% larger than the FMVSS, respectively. The reason why the FMVSS presents a much more severe HIC is because the barrier is a rigid anchored wall instead of an ODB that also absorbs a significant part of the energy, representing the deformation on other vehicle. Moreover, the overlap in the FMVSS is total, which means that the structure does not have much room to pitch and yaw. This can be seen from the percentage of dissipated energy. This means that the shock is perfectly plastic (practically) and only a small rebound is observed. For the 96/79/EC and EURONCAP simulations, in which the obstacle overlap is 40%, the structure may pitch, yaw and rebound thanks to the generation of a moment around its centre of gravity. Another parameter that shows the rate of how the energy is being dissipated is the maximum acceleration, which is significantly larger for the FMVSS case. Furthermore, the ODB allows the impact to last for a longer period of time, decreasing the HIC considerably.

4.4. Analysis on the influence of speed

Simulations were run at different speeds using the same model as the one used for the FMVSS. This time, the frame thickness of 1/8'' seemed appropriate, precisely due to its flexibility. This will be used to highlight the effects of speed in a crash. It must be noted that, in the FMVSS simulations the block mass at the back did not hit the barrier. Plots of the acceleration *vs* time as well as HIC and % of dissipated energy *vs* speed are presented in figure 7.

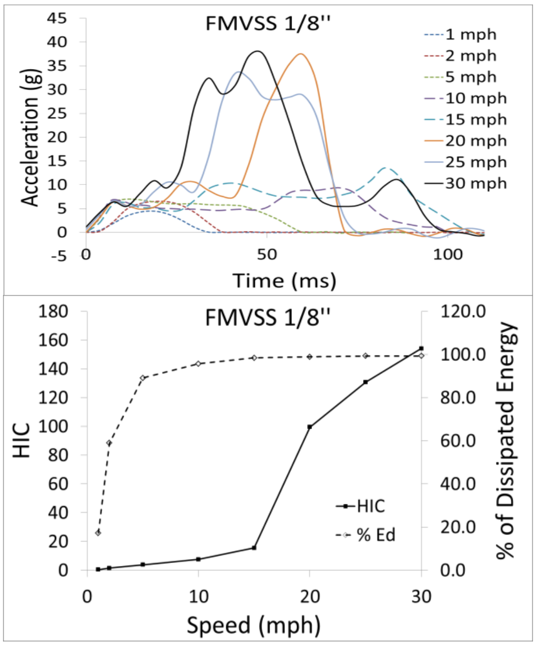

Fig. 7 Plots of the acceleration vs time during the impact at different speeds (above) and plot of the HIC and percentage of dissipated energy vs speed (below) for the FMVSS like protocol.

First, from the acceleration *vs* time plots, it is possible to observe that there are three groups of results: very low speeds (1, 2 and 5 mph), low speeds (10 and 15 mph) and moderate speeds (20, 25 and 30 mph).

In the first group (very low speeds of 1, 2 and 5 mph), the maximum level of acceleration is low (around 5g) and lasts for a relatively small period of time. The shock is elastic (the structure rebounds), which can also be seen from the low levels of dissipated energy, especially for 1 mph. However, because it is the frame alone that is being simulated, with no other components (like the engine, mounts, padding, etc.), some plastic deformation may have already occurred.

In the second group (low speeds of 10 and 15 mph), the maximum level of acceleration still is quite low (around 10g), but it lasts for a much longer period of time. However, the HIC, although higher than before, still is quite low: less than 15.

It is on the third group (moderate speeds of 20, 25 and 30 mph) that there is a considerable shift in the structure's response. First, there are now considerably larger peaks for the acceleration, reaching 38g for an initial speed of 30mph. Also, the deceleration period lasts for a larger period of time. The HIC reached values as high as 154.

Although the model provides an approximation of the response of the F150 frame under impacts, especially at slow speeds (no initiators or other devices like crush-cans were included), it shows how the frame is working for slightly higher speeds. By deforming plastically while at the same time holding some stiffness, it restricts the acceleration peaks and extends the time interval to levels that make the impact more likely to be tolerable to the human body.

5. Conclusions

A simulation of the the frontal collision of a car frame using non-linear FEA has been presented. Three frontal crash situations were evaluated, mimicking the FMVSS no.208, the 96/79/EC and the EURONCAP tests. The model of the chassis used in the simulations – a Ford F150 - is based on one that was previously studied in another journal paper [8]. However, in that paper, the simulation only considered a static load on the bumper (a pressure) and the conclusions do not reflect what would happen during a real impact. From the simulations that have been run in this paper, which are by no means exhaustive, it appears there are some stark differences between this paper and the original one. Although there is overlap and agreement in areas such as the profile of the pressure against time at the beginning of the impact [15], it seems from the images in [8] that there is far too little deformation occurring in the model, which means little agreement with a real impact scenario. In this paper, the profile of deformation in the simulations run is comparable to the deformation which is visible in the videos of real tests, even if important components, like the engine, have not been considered in the simulations.

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