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# Effect of Transverse Load on Energy Absorption of a Vehicle Frame During Accident: a Finite Element Analysis

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***Abstract*—A finite element model was introduced to simulate the experimental data of an axially loaded column subjected to a transverse load [1]. The model was validated and proved to be in good correlation with the experimental results. The model was further used to investigate the effect of applying a transverse load on axially loaded members of a vehicle frame. Results showed that the energy absorbed by theses members increased due to buckling deformation being enlarged as a consequence of this transverse impact. Also effect of time delay between axial load and transverse load application has been investigated. Results showed that applying transverse load with time delay of about 15 ms increase absorbed energy absorbed by previous members.**

***Keywords—bus frame design; impact energy absorption; car accident; vehicle safety; impact analysis***

## I. INTRODUCTION

Safety is the main challenge now in vehicle industry. Generally modern vehicle frame is designed so that, when an accident occurs, vehicle frame collapses within the crushable zone to absorb the impact energy, so that the passenger is isolated from being subjected to such energy. Of course many active and passive safety systems are used in modern vehicles, for example seat belts, air bags….etc. during accident, there is a very important issue which is the effect of collision on the internal organs of the passenger. During steady state motion of the vehicle, for example at 100 Kph, vehicle, passenger body are moving with the same speed, when an accident occurs, vehicle speed decreases (many parameters affects the accident like obstacle state, speed, direction) from steady state speed to a low speed which might be zero speed in very short time. Acceleration is rate of change of speed, so in accident situation passenger body is subjected to a sever value of deceleration that may lead to damage in internal organs of passengers inside the vehicle. Another issue during accident faces the passengers, which is the large amount of deformation in vehicle body which may be the reason of severe injuries and death even at low speed range [2]. The most common method to collapse a vehicle is to reduce its structural stiffness by adding imperfections to the structure, for example dents, and bends. On the other hand, during vehicle operation high stiffness of the structure is required as a primary design specification and to give a better driving performance, and to reduce vibration and noise. In practical design, stiffness must be compromised to satisfy both requirements simultaneously.

Since vehicle speed and driving comfort is expected to continuously increase in future, higher stiffness of the structure will be very important parameter. Therefore, it will be very important to maintain high stiffness while improving the energy absorption using alternative methods [3].

The common shapes of collapsible energy absorbers and the different modes of deformation of the most common ones were investigated. Common shapes include circular tubes, square tubes, frusta, struts, honeycombs, and sandwich plates. Common modes of deformation for circular tubes include axial crushing, lateral indentation, lateral flattening, inversion and splitting. Main objective was to compare the performance of each shape relative to other shapes [4].

A thin-walled circular tube of mean radius R and thickness H, when subjected to an axial force, may develop either axisymmetric buckles, or a non-axisymmetric (diamond) pattern. Various theoretical methods predict that thicker tubes with $R/H < 40–45$, approximately, deform axisymmetrically, while the thinner tubes, with larger values of R/H, buckle into a non axisymmetric mode. However, some tubes may switch, during a test, from an axisymmetric deformation mode into a diamond pattern [5-9].

Quasi-static and dynamic axial crushing tests were performed on thin-walled square tubes and spot welded top-hat sections made of high-strength steel grade DP800. The dynamic tests were conducted at velocities up to 15 m/s with an impacting mass of 600 kg in order to assess the crush behavior, the deformation force and the energy absorption. Typical collapse modes developed in the sections and the associated energy absorbing characteristics were examined and compared with previous studies on high strength steel. A significant difference was observed between the quasi-static and the dynamic crushing tests in terms of the deformation force and impact energy absorption. As this difference is attributed to strain rate and inertia effects, material tensile tests at elevated strain rates have been carried out. A comparison is made with analytical methods and the response was under-predicted. In addition, numerical simulations of the axial crushing of the thin-walled sections were performed and comparisons with the experimental results were satisfactory. The validated numerical model was used to study the energy absorption capacity of thin walled sections with variations in the yield strength, sheet thickness, flange width and spot-weld spacing.

Structural effectiveness differences have been captured through simulations between spot-welded top-hat sections made of mild steel and high-strength steel [10].

Steel tubes are widely encountered in industrial applications and are commonly exposed to accidental loads. Collision between supply ships and the legs and bracing members of offshore oil rigs, impact of heavy dropped objects on these members, mishandling during the launching and installation of marine structures, explosions and collision of moving ice sheets with offshore structures are examples of such accidents. Prior to an accident, tubular structural members will be carrying their normal operational loads.It is very important that this service load (pre-loading) is considered when the effect of impact damage is going to be estimated.

Experimental studies were done, in which axially pre-loaded tubes were examined under lateral dynamic impact loads. The tubes were impacted by a dropped object with a velocity of about 7 m/s at their mid-span. The experimental investigation was aimed at gaining an insight and understanding of the dynamic failure and behavior of the impacted tubes and to provide bench-marking data on the response of axially loaded steel tubes subjected to lateral impact [11].

Improvement of energy absorption of impacted column by applying transverse impact load was investigated. Experimental test was done on various specimens, axial deflection, axial load and absorbed energy was compared to evaluate the performance of this method of improvement of energy absorption [1].

The effects of factors affecting energy absorption of tubes such as impact velocity, strength, temperature and tube geometry were investigated by (Kim et al and Vankuren et al, compared the collapse absorption capacity of hydroformed, as-received and press formed tubes. Results demonstrated that hydroformed tubes showed the highest value [12, 13]. Lin et al investigated the modeling of hydroformed tubes during crash. The study provided simplified models that achieved feasible correlation with actual tests [14]. Modeling of tubes in crash was also studied by Palonivelu et al [15].

Cosme et al discussed the integration of computer aided design and engineering software codes (Pro/Engineer, ADAMS and ANSYS) to simulate the effect of design changes to truck frame [16]. Galipeau-Belair et al investigated the design and testing of side under-ride protection devices for tractor-trailers and straight trucks [17]. Crivellaro et al studied the effect of frame flexibility on commercial vehicle performance [18].

In this paper, the effect of transverse load on absorbed energy by vehicle frame members was investigated. A finite element model was validated, by comparing finite element model results with the experimental results [1].The same model was used to evaluate the effect of transverse load value, and the applying time of the transverse load relatively to the axial load application, on the collision energy absorbed by axially loaded bus frame member.

## II. FINITE ELEMENT MODEL

A transverse vertical load is applied to the axially loaded vertical column, as shown by Figure 1.A finite element model was proposed to simulate the experimental setup shown in Figure 2 that was used by Sastranegara et al [1].

Two cases were studied. In the first case, the axial velocity $v_a$ was 2.6 m/s and the transverse velocity $v_t$ was 5.3 m/s, while the time delay $t_T$ between axial and transverse loads was taken as 0.5, 3.2 or 5.4 m/s. In the second case, $v_a$ was 3.5 m/s, $v_t$ was 5.3 m/s and $t_T$ was 0.4, 4.1 or 8 m/s. ANSYS software (explicit) version 14.5 was used in this study. Figure 3 shows the 3D model that was introduced, while Figure 4 shows a typical output result obtained from the analysis.

Comparison between experimental and theoretical results showed the same trend and a good correlation as shown in Figure 5 to Figure 9. Note that the peak value of axial load time is different from the experimental peak time due to change in the zero reference, in simulation at time= 0 sec, the axial impactor starts touching the top rubber plate above the specimen with the analysis axial velocity 2.6 m/s and 3.5 m/s, while this condition is not applicable in experimental results because impactor can't accelerate in zero time, it must consume some time to reach impact velocity.

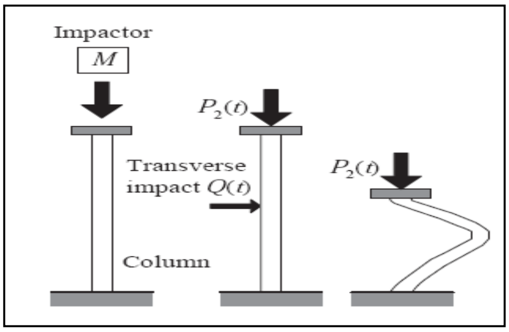

Fig.1. Proposed method used to improve impact energy absorption [1]

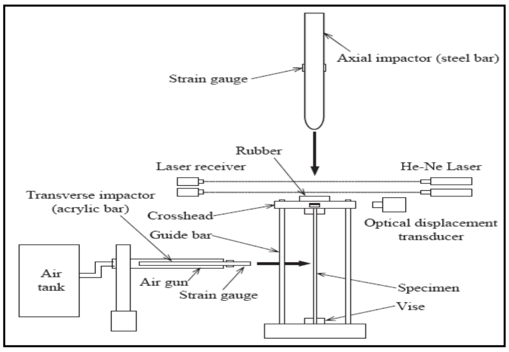

Fig.2. Experimental setup [1]

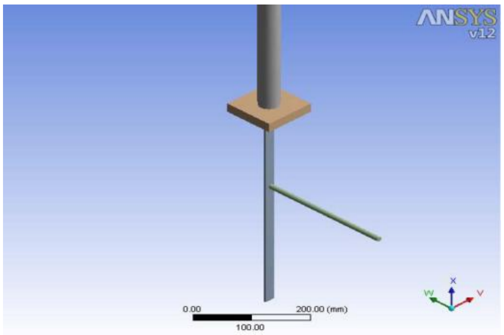

Fig.3. 3D model used in validation process

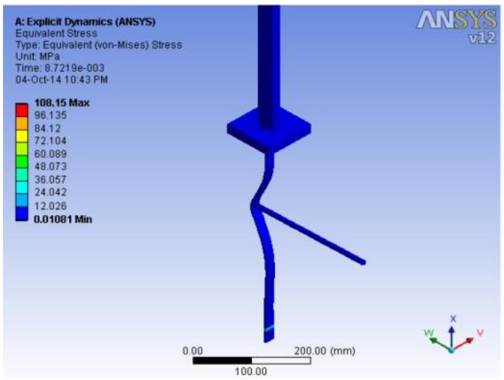

Fig.4. Typical output results for the analysis

Also as shown in Figure 2 there is a time lag between axial speed measurement and touching the rubber plate above the specimen. Effect of $t_T$ in simulation results correlate with the experimental results.

The absorbed energy is the area under the P-u curve, hence the absorbed energy can be calculated from the following relation

$$E_{ab} = \int_0^u P(u)\,du,$$

Where:

$E_{ab}$ : absorbed axial impact energy
P(u) : axial load
u : axial displacement

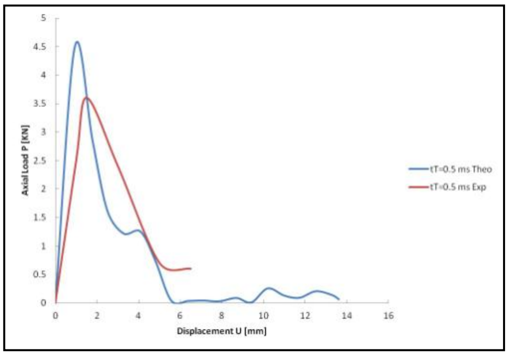

Fig.5. Load displacement curves for $V_a$=2.6 m/s and $V_t$=5.3 m/s, $t_T$=0.5 ms

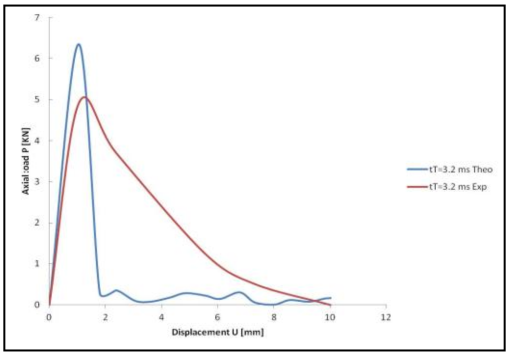

Fig.6. Load displacement curves for $V_a$=2.6 m/s and $V_t$=5.3 m/s, $t_T$= 3.2 ms

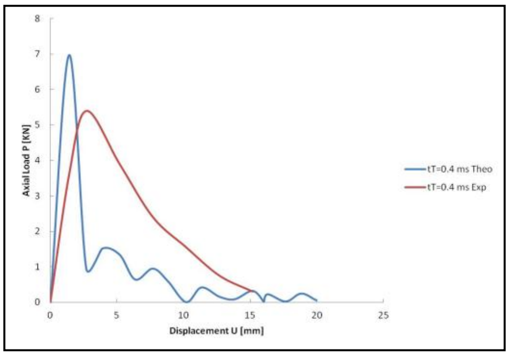

Fig.7. Load displacement curves for $V_a$=2.6 m/s and $V_t$=3.5 m/s, $t_T$=0.4 ms

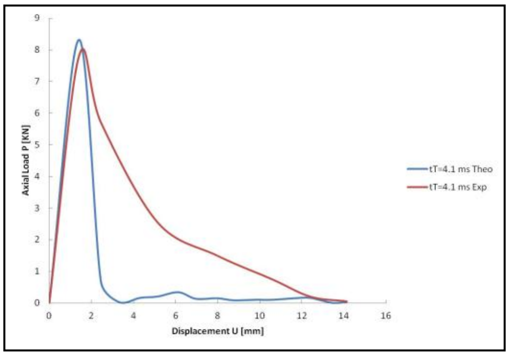

Fig.8. Load displacement curves for $V_a$=3.5 m/s and $V_t$=5.3 m/s, $t_T$=4.1 ms

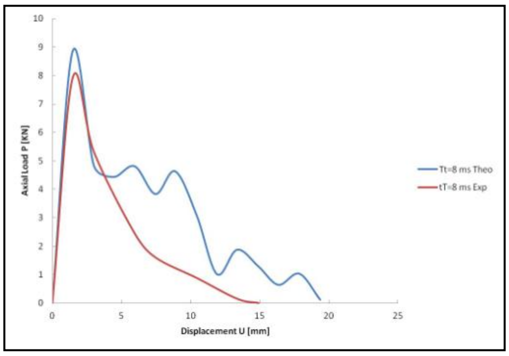

Fig.9. Load displacement curves for $V_a$=3.5 m/s and $V_t$=5.3 m/s, $t_T$=8 ms

## III. EFFECT OF TRANSVERSE FORCE VALUE ON ABSORBED ENERGY BY AXIALLY LOADED VEHICLE FRAME MEMBERS

### A. *Introduction*

The main aim of this investigation is to evaluate the effect of the magnitude of the transverse load and its application time on the energy absorbed by axially loaded vehicle frame members. This data can be used to develop a system similar to an air bag system, but instead of triggering the air bag during an accident, a force actuator is operated so that a transverse force is applied with a certain value, at a given application time, at specific points on the frame. In this case two targets are achieved which are, improving accident energy absorption during accident, while maintaining frame rigidity during operation. This will control the frame deformation so that no injuries or death occur as a result of the large deformation of frame members. So in the next section, a transverse force will be applied to axially loaded tubes of a bus frame. The effect of the magnitude of the transverse force and the application time on energy absorbed by these members will be evaluated.

### B. *Model preparation*

For this investigation, a driver side window frame was taken to be subjected to an impact mass with velocity 10 m/s. Frame was made of steel ASTM A36 rectangular tubes, is a part of a complete bus frame. The complete frame is shown in Figure 10 while the investigated part is shown in Figure 11.

ANSYS explicit version 14.5 was used, boundary conditions and transverse force location, members names are shown in figure 12, while the impactor speed is shown in figure 13.

Transverse force values were taken between 200 and 1000 N with a step of 100 N, application time or $t_T$ was taken to be 0, 5 ,10,15 and 20 ms. I7 PC with 24 GB of ram memory was used, each individual case needed about 8 hours to be completed. Analysis results are shown in Figure 14 to Figure 21 for the upper and lower members of the bus frame.

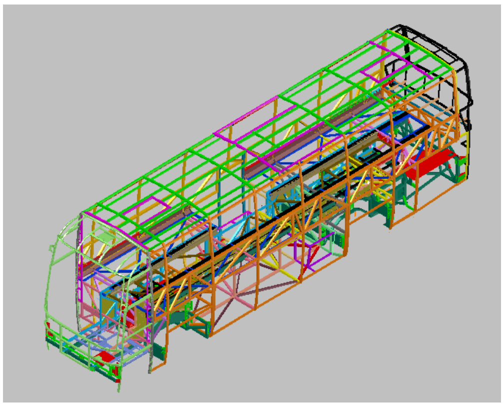

Fig.10. Complete bus frame model used in this investigation

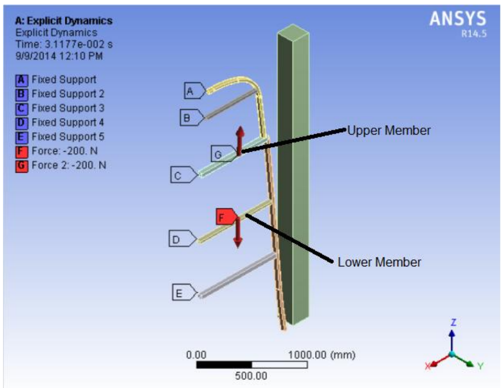

Fig.11. Part of frame used in this investigation

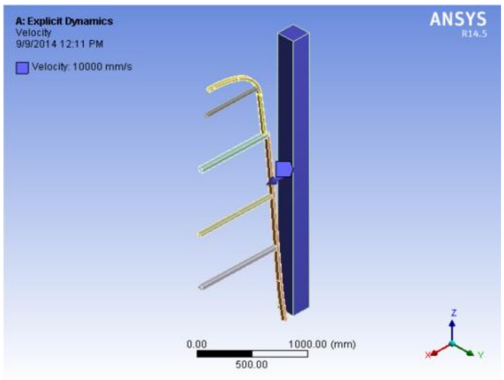

Fig.12. Boundary conditions and transverse load value, application points

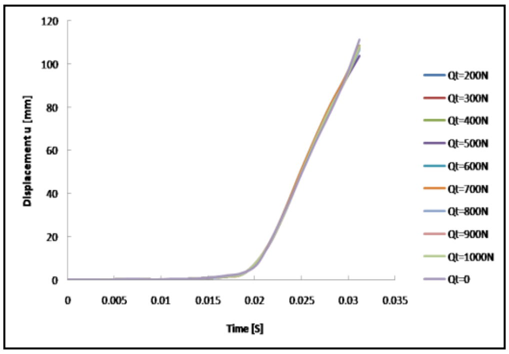

Fig.13. Impactor speed and direction of motion

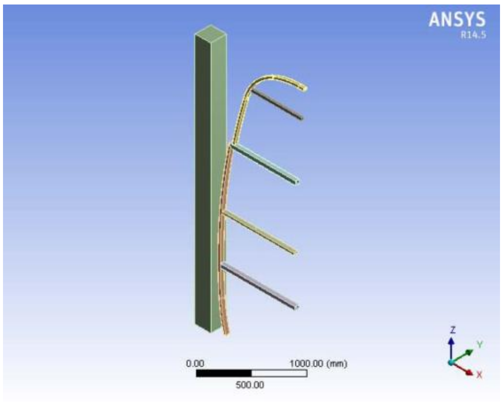

Fig.14. Upper member displacement u with time

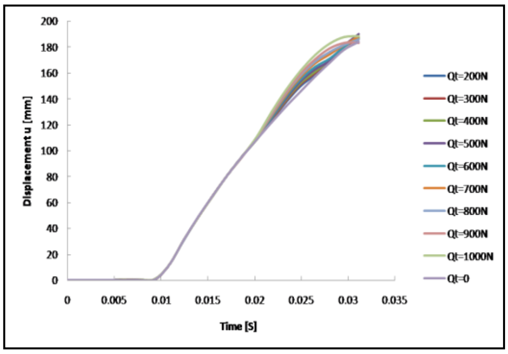

Fig.15. Lower member displacement u with time

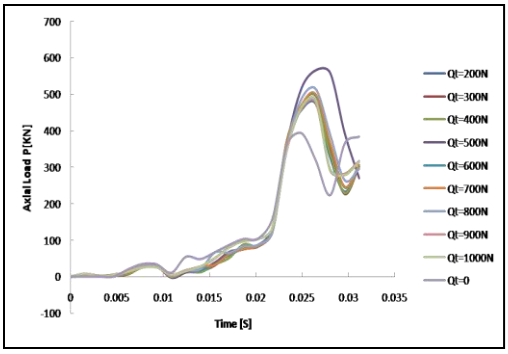

Fig.16. Upper member axial force P with time

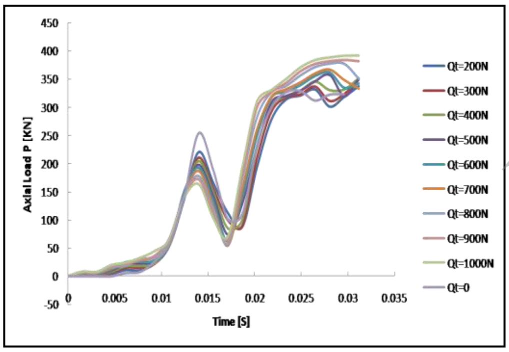

Fig.17. Lower member axial force P with time

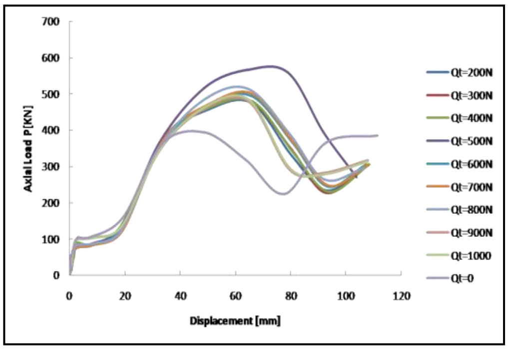

Fig.18. Upper member load displacement curve

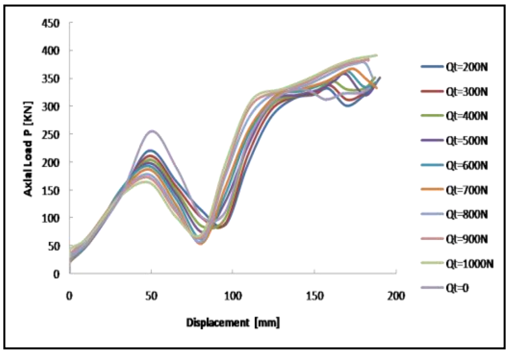

Fig.19. Upper member load displacement curve

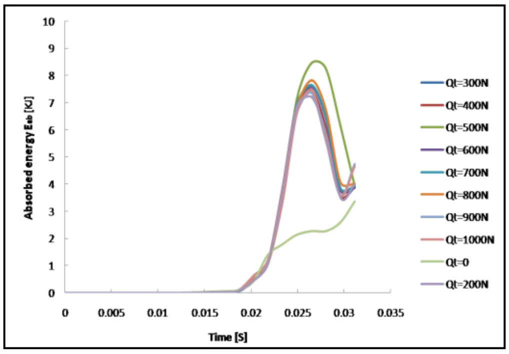

Fig.20. Absorbed energy by upper member with respect to time

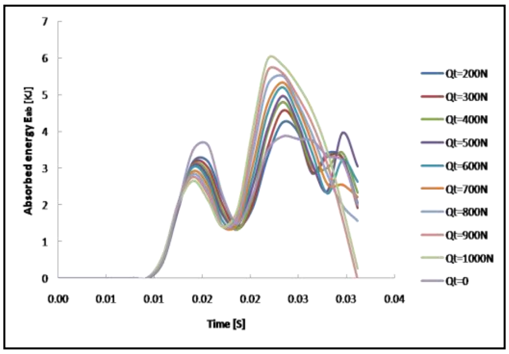

Fig.21. Absorbed energy by lower member with respect to time

### C. Results discussion

As shown in previous figures, applying a transverse force to axially loaded members of a bus frame has a local effect that varies from member to member. Figures 14 and 15 show the effect of the transverse load on member displacement with respect to time. It is seen from Figure 14 that applying a transverse load to the upper member has a negligible effect on its displacement, while applying the same transverse load to the lower member has a noticeable effect on the lower member displacement. Generally, the effect of transverse load on member displacement appears after axial loading starts by a time delay. Figure 15 shows that the effect of transverse load on deflection starts after 20 ms from start of collision. Applying transverse load leads to an increase in the member displacement. Other parameter affecting the value of member displacement while applying a transverse load are the cross section of the member, its cross section . direction of application of the transverse load. The upper member is a square tube with cross section

50X50X2 mm, while the lower member cross section is a rectangular tube with cross section 50x30X2 mm. For the lower member, the transverse load was applied about the axis of minimum moment of inertia, so that it has a greater effect on the lower member than the upper member.

Figures 16 and Figure 17 show the effect of transverse load on the value of axial force acting on the upper and lower members. External work by axial impact was lost by the post buckling behavior of the specimen. As shown in figure 16, applying 500 N transverse load to the upper member increases the axial load from 318 KN to 566 KN at 26.5 ms. Also for the lower member applying 1000 N transverse force increases the axial load from 318 KN to 383 KN at 26.5 ms. For both upper and lower members, it is confirmed that the effect of the transverse load appears on members after a conversion point. Before this point, the transverse load has no effect on the axial force value, while after the conversion point, its effect appears as shown in the previous figure. As discussed before, transverse load has a local effect on each individual member. Many parameters control this effect as discussed before, as well as other parameters like the nature of collision and its direction. The optimum value for the transverse load is 500 N, while the optimum value for the lower member is 1000 N As shown in figure 16.

The same concept is applied on results shown in Figure 18 and Figure 19. Values of previous figures were used in equation 3 to get the energy absorbed by the mentioned members. It is clear from Figure 20 and Figure 21 that applying a transverse force affects the value of absorbed energy due to impact. As mentioned before, the optimum value for best energy absorption for the upper member is 500 N, while the optimum value for lower member is 1000 N. In Figure 20, applying 500N transverse load increases the energy absorbed by the upper member due to impact, from 2.27 KJ to 8.45 KJ at 26.5 ms. For lower members, applying 1000N transverse load increases the energy absorbed by the lower member from 3.74 KJ to 4.55 KJ. This is our target to increase the absorbed energy during impact, while maintaining the frame rigidity at steady state operating conditions.

## D. Effect of transverse force application time on the absorbed energy

Figure 22 shows that applying a transverse load with a time delay of 10 ms increases the absorbed energy from 2.27 KJ with no transverse load to 7.2 KJ with 200 N transverse load at time 26.5 ms. For the upper member, as shown in figures 22, 24, 25 and 27, there is only one peak for absorbed energy value. At this peak, only one delay value is the optimum, it various between 5 and 15 ms. For the lower member, there are 2 peaks, the first peak is about 15 ms after start of the collision At this peak the transverse load has no effect on the energy absorbed by the lower member, while at the second peak, which is about 23 ms from start of the collision, applying a transverse load leads to energy absorption improvement, also making a time delay improves the absorbed energy. For both upper and lower members, a time delay of 20 ms decreases the energy absorbed by the upper and lower members, so that for 32 ms collision time, the optimum delay should not exceed 15 ms, i.e. in order to improve the energy absorption due to transverse load, time delay between start of collision and application of the absorbed transverse load should not exceed 50% of the axial loading cycle time.

Using data in this paper can help improve a new vehicle safety system similar to the system used in air bags. Instead of triggering the air bag actuator, the force actuators engaged to the bus frame, at an accident condition, can apply a transverse force to certain members in the frame, so that impact energy absorption is improved. Frame deformation is also controlled so that a space for passengers is maintained without the hazard of being injured or killed by uncontrolled frame members deformation. Dampers can be inserted between bus frame members for this purpose. When an accident occurs, the damper is subjected to an instantaneous velocity which can be used as a source of transverse load instead of force actuator.

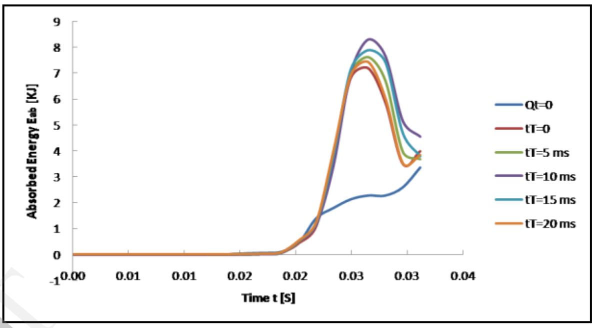

Fig.22. Effect of $t_T$ on energy absorbed by upper member, Qt=200 N

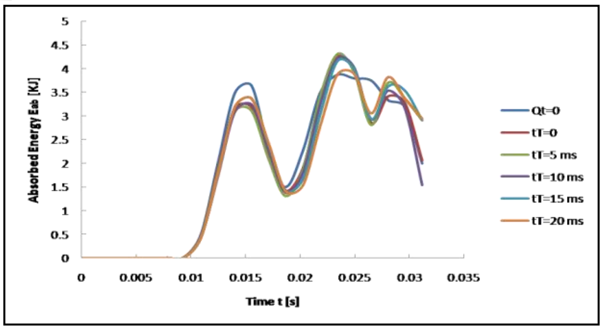

Fig.23. Effect of $t_T$ on energy absorbed by Lower member, Qt=200 N

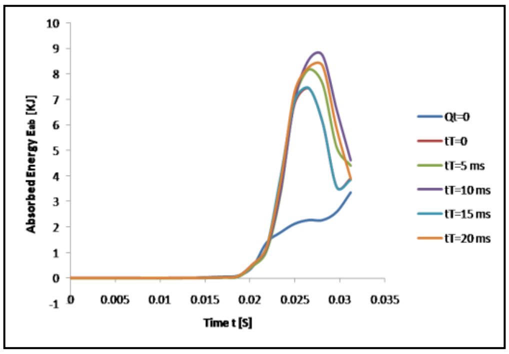

Fig.24. Effect of $t_T$ on energy absorbed by upper member, Qt=300 N

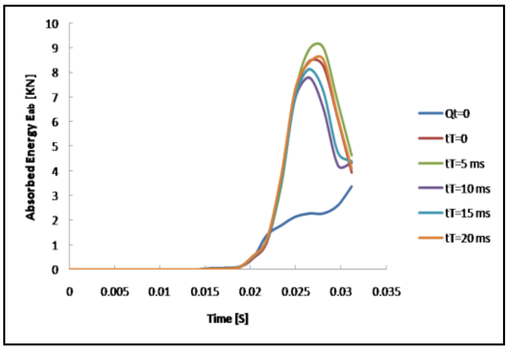

Fig.25. Effect of $t_T$ on energy absorbed by upper member, Qt=500 N

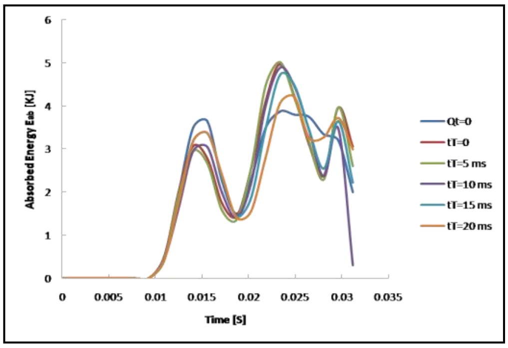

Fig.26. Effect of $t_T$ on energy absorbed by lower member, Qt=500 N

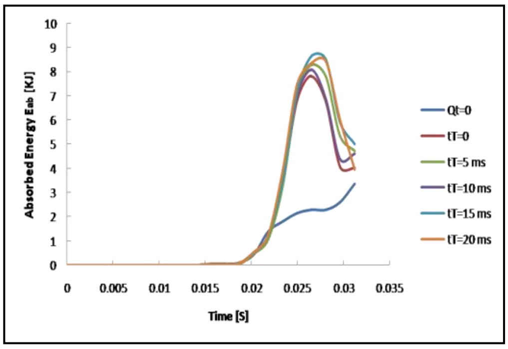

Fig.27. Effect of $t_T$ on energy absorbed by upper member, Qt=800 N

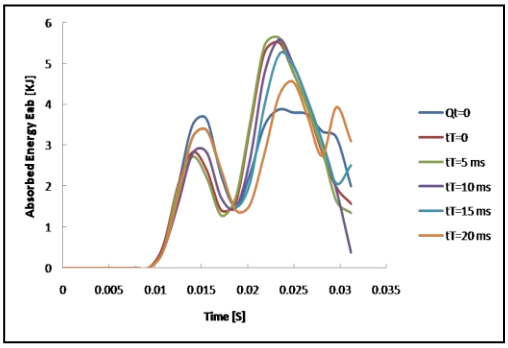

Fig.28. Effect of $t_T$ on energy absorbed by lower member, Qt=800 N

## IV. CONCLUSION

The effect of a transverse impact load applied to axially loaded bus frame members was investigated. A finite element model was introduced and validated, and was further used to investigate the effect of transverse force magnitude and application time on energy absorbed by two bus frame members during an accident. Analysis results show that applying a transverse load improved energy absorbed by these members by values various from 20% up to 270%

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