Impact of Seat Belts on the Structure of a Typical Transit Bus

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A finite element computer model was developed for the structure of a typical transit bus used by smaller cities and rural communities. Assumptions were made regarding the loading conditions of the bus in the event of a rapid deceleration of the bus. Parametric results for floor angles of 0 to 30 degrees at maximum bus deceleration were derived for two loading patterns: (*a*) with seat belts installed on all passenger seats and (*b*) with seat belts installed on the front passenger seats only. The results indicated that the structural members in the bus frame could experience moderate to substantial decreases in maximum stress if seat belts are installed on all seats, whereas the structural members in the chassis could experience moderate increases in maximum stress if seat belts are installed. Thus the presence and presumed use of seat belts on all passenger seats in the event of a rapid deceleration of the bus should moderately to substantially benefit the structural frame members of a typical transit bus, and the absence of seat belts should moderately benefit the structural chassis members.

A study is under way at the Department of Civil Engineering, Wayne State University, to assess the safety and structural implications of seat belt installation on a typical transit bus used by smaller cities and rural communities. One of the objectives is to determine whether changes in the structural members of the bus may be warranted to enable the structure to better withstand any additional accident-induced member stresses caused by the presence of seat belts. A computer-based finite element structural model of a fully loaded transit bus was developed to analyze the forces generated within the structural members of the bus because of the maximum expected deceleration applied to the mass of the bus passengers. Two loading patterns, with and without seat belts, were analyzed using a 20-*g* bus deceleration. The results were used to estimate the differential member stresses caused by the presence of seat belts as a function of the bus deceleration.

A comprehensive literature review conducted as a part of the project indicated little, if any, research into the behavior of the structural components of a bus following a sudden bus deceleration. Thus the analyses presented are to be considered the first that have been performed on a transit bus. The terminology concerning the components of a transit bus and the structural implications of a rapid bus deceleration with and without seat belts are discussed.

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TERMINOLOGY

In the discussions that follow, "body" refers to the outer shell of the bus, consisting of the sidewalls and roof. "Floor" describes the plywood and metal deck upon which the passenger seats rest. "Frame" refers to the cold-formed steel members that support the body and floor and that are constructed by the bus manufacturer. "Chassis" describes the portion of the bus that supports the bus frame, engine, drive train, axles, and so forth and is built separately by a truck chassis manufacturer.

CRASH TESTS

Over the years, reports dealing with head-on crash tests of school and transit buses have concentrated on the visible damage to the buses tested. The three principle types of visible damage that have been reported are

1. Detachment of passenger seats from the bus floor (*1–4*),
2. Slippage of the bus frame-to-chassis connections (*1,5,6*), and
3. Buckling of the bus floor (*1,2,4*).

The connections involved in the first two types of visible damage tend to be unique to each transit bus design, are more easily corrected, and are not in general relevant to the overall structural integrity of a transit bus. The third type of visible damage is more a structural type of failure, however.

Most crash tests appear to have been done using buses with metal floors, although few researchers specifically mention the bus floor materials. Both the full-size school bus crash tests by the University of California, Los Angeles (*1*) and the crash tests of large transit buses by the General Motors Corporation (*2*) indicated that the bus floors "buckled" in head-on collision tests. This implies that the floors were made of metal, because plywood is expected to splinter, not buckle. The crash responses of the remaining structural components of the buses tested were not reported, however. Therefore, the goal of the present study was to analyze the potential for structural damage to a typical transit bus under rapid bus deceleration.

COMPUTER MODELING

One previously reported use of finite element computer modeling in the analysis of transit buses was a series of models developed by DAF Trucks, Eindhoven, the Netherlands (7). The goal of these analyses was to measure the effects of bending stiffness and torsional stiffness on the dynamic responses and, hence, the ride comfort of bus passengers. Seven finite element models were developed, each using about 2,700 degrees of freedom. The major differences in these models centered on the designs of the lower sidewalls (the areas of the sidewalls below the windows) and the adhesive materials used to bond the windows to the bus sidewalls. Each model was analyzed to determine its fundamental natural frequencies. The natural frequencies were used to estimate the "comfort level" of the bus passengers. No analyses under simulated accident loads were performed, however. The goal of the study presented here was to use finite element computer modeling to analyze the potential for structural damage to a typical transit bus in the event of rapid bus decelerations (simulated front-end impacts).

MODELS AND ASSUMPTIONS

The thrust of the research has been to develop and analyze a finite element computer model of the structure for a typical transit bus used by transit agencies in smaller cities and rural communities. The model consists of the bus seats, plywood floor, steel frame, and steel chassis for the bus chosen. The model includes the deceleration forces generated by the mass of each passenger applied at the location of the average adult center of gravity (CG). The model was analyzed to determine the maximum stresses in each structural component of the bus under various loading conditions. The finite element code used in these analyses is the ANSYS finite element program, which is a product of Swanson Analysis Systems, Inc., Houston, Pennsylvania.

Transit Bus Studied

The transit bus that was analyzed is 25 ft long and has 13 passenger seats, for a total seating capacity of 26 passengers plus the driver. Longitudinal and transverse cross-section views of the bus seats, floor, frame, and chassis are shown in Figures 1 and 2, respectively. The seats are fabricated from cold-formed tubular steel and are supported by two inverted T legs bolted to the bus floor. The bus floor is composed of exterior grade plywood with steel strapping reinforcing along the lines where the seats are bolted to the floor and along the plywood seam that follows the centerline of the bus floor. Sheet metal reinforcing is also used in the tops of the rear wheel wells.

The bus floor is supported by lateral frame members, which are fabricated from cold-formed steel channels. The lateral

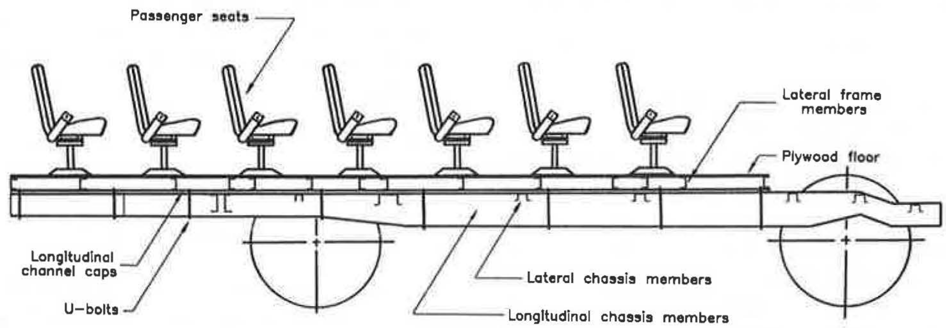

FIGURE 1 Longitudinal cross-section view of bus structure.

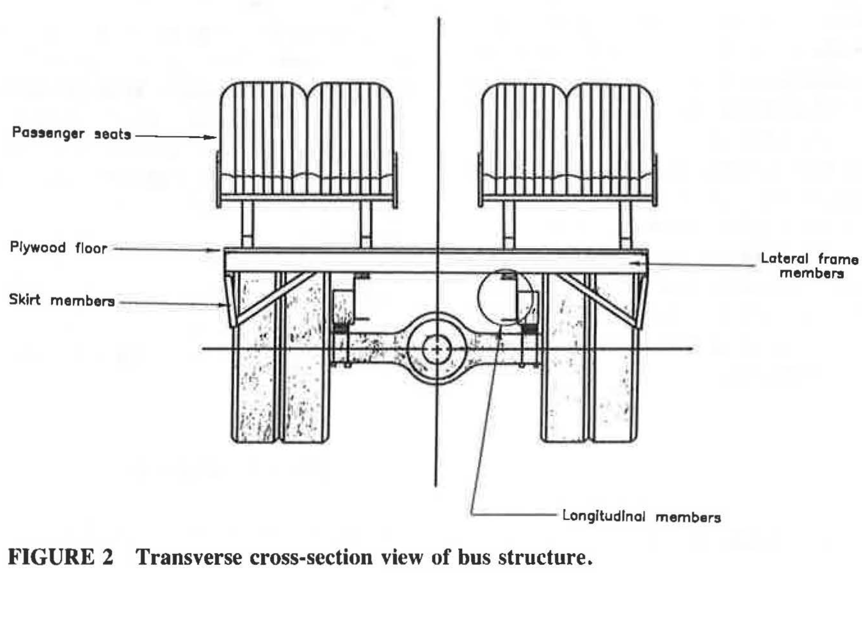

FIGURE 2 Transverse cross-section view of bus structure.

frame members run between the sidewalls of the bus and support the body, floor, and frame of the bus. Cold-formed steel members are also used for the side skirting and other frame members around the perimeter of the bus floor. The lateral frame members are welded to longitudinal channel caps, which are in turn attached to the chassis with U-bolts. The chassis is composed of two longitudinal members fabricated from cold-formed steel channels. The longitudinal chassis members are connected at intervals by lateral channel struts.

Simplifications and Assumptions

A perspective view of the bus model excluding the bus floor and seats is shown in Figure 3. The simplifications and assumptions that were made in developing the model were as follows:

1. To concentrate on the bus responses caused by the mass of the bus passengers under rapid deceleration (and hence the effects of seat belts), the following were excluded from the bus model: engine, drive train, air-conditioning unit, steering components, suspension components, and driver's seat. To further simplify the model and because the passenger seats are not bolted to the sidewalls, the sidewalls, backwall, and roof of the bus were not included in the bus model. In addition, the stairs, battery tray, and other steel reinforcing members that are not directly attached to the plywood floor were also excluded from the bus model.

2. The seats were each modeled using five semirigid (high-stiffness) elements as shown in Figure 4. The elements were arranged like a swing set, with one horizontal semirigid element connecting the nodal points representing the CG of the two passengers in the seat and two diagonal semirigid elements connecting each of these CG nodal points to the bus floor at or near the points where the actual bus seats are bolted to the bus floor.

3. The plywood floor was modeled using plate finite elements as shown in Figure 5. The plywood floor was modeled as continuous without any seams. Thus the steel strapping along the centerline of the bus floor was not included in the model. The steel strapping along the bolt line of the seats and the sheet metal reinforcing in the rear wheel wells were modeled using plate elements as shown in Figure 6. The steel plate elements are superimposed on an outline of the bus floor in Figure 6.

4. To maintain a maximum 2:1 ratio for the longest to shortest dimensions of the plate elements representing the plywood floor, steel strapping, and sheet metal, some nodes corresponding to seat bolt locations were moved longitudinally to coincide with node locations on transverse frame members. The nodes were moved in such a manner that the original spacings between bolts on each seat leg were unaffected.

5. The transverse frame members, perimeter frame members, and longitudinal channel caps were all modeled using beam finite elements as shown in Figure 3. For simplicity, the centroids of the beam elements were all placed in the same horizontal plane as the plywood floor and steel plate elements. To model the vertical offset between the lateral and perimeter

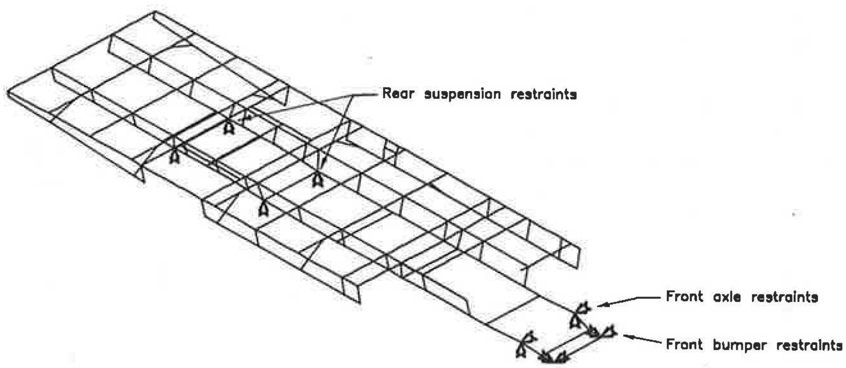

FIGURE 3 Bus model excluding floor and seats.

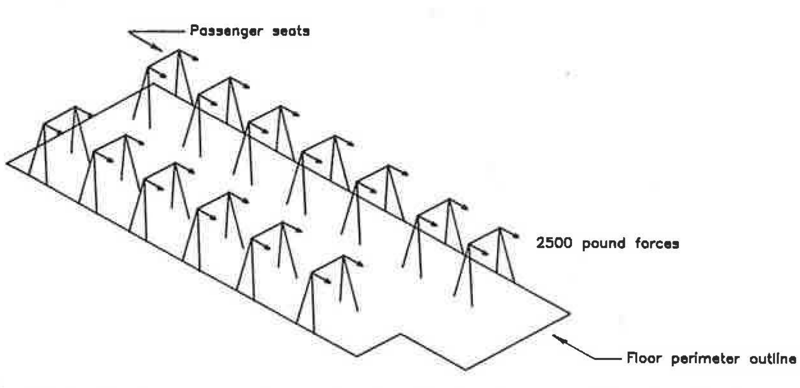

FIGURE 4 Passenger seats and load application for bus with seat belts.

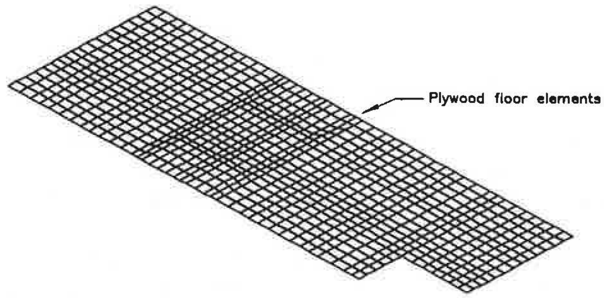

FIGURE 5 Plywood floor elements.

frame members and the plywood floor and steel plate members, 300 semirigid elements would have been required. These additional elements would have caused the model to exceed the storage capacity of the computer that was used in the analyses.

6. The longitudinal and transverse chassis members and the skirting members were also modeled using beam elements as shown in Figure 3. Figure 3 also shows semirigid elements that were used to connect the transverse frame elements with the centroid of the longitudinal chassis members at the points where the transverse frame members are welded to the longitudinal channel caps. Thus each longitudinal chassis member is attached to lateral frame members at 14 locations. In the actual bus, each longitudinal chassis member is attached to the corresponding longitudinal channel caps by eight U-bolt connections. Additional lateral-torsional buckling support for the longitudinal chassis members is provided by nine transverse chassis members. The maximum unbraced length of each longitudinal chassis member in the model is 26 in. versus 32 in. in the actual bus. Because this 32-in. distance is at the rear of the bus where the compressive forces in the longitudinal chassis members would be lowest under rapid deceleration, the effects of any increased buckling resistance of the model versus the actual bus should be relatively small.

7. The front leaf springs are assumed to "bottom out" in the event of a rapid bus deceleration. Therefore, as shown in Figure 3, the front of the bus was modeled with vertical and transverse pin connections at the points where rubber stops are attached to the longitudinal chassis members to prevent damage due to bottoming out of the front axle. Figure 3 also shows transverse and longitudinal pin connections that were used at the front of the longitudinal chassis members where the front bumper is attached.

8. Vertical pin connections were also used at the points where the rear leaf springs are attached to the longitudinal chassis members (Figure 3). The connections are necessary to prevent rigid-body motion of the bus model.

LOAD CASES

To simulate the loads generated by the passengers under rapid deceleration, a maximum force of 2,500 lb was assumed for each passenger, the same force required by the Federal Motor Vehicle Safety Standards (*8*) for testing bus seats. If an average passenger weight of 125 lb is assumed, the deceleration required to generate a 2,500-lb force is 20 *g*. The 2,500-lb forces were applied using seven different angles of the bus floor from 0 to 30 degrees at maximum bus deceleration. The bus floor angles were simulated by "tilting" the 2,500-lb forces as opposed to tilting the entire bus model. The vertical and longitudinal force components that were used to simulate each bus floor angle are given in Table 1.

The angle of the bus floor at maximum deceleration should remain below 5 degrees until the total vertical reaction forces at the rear axle pin connections exceed the maximum loaded weight of the rear axles. For the bus with seat belts this occurs at about 17 *g*, and for the bus without seat belts this occurs at about 15 *g*. At higher levels of maximum deceleration, the floor angle of the bus will exceed 5 degrees, and the total vertical reaction forces at the rear axle will exceed the maximum possible. Thus the member stresses in this region could have inaccuracies at bus decelerations greater than 17 *g* for the bus with seat belts and 15 *g* for the bus without seat belts.

The two seat belt configurations considered were (*a*) with seat belts installed on all passenger seats ("the bus with seat belts") and (*b*) with seat belts installed on the front passenger seats only ("the bus without seat belts"). The loading pat-

TABLE 1 LOAD CASES

Bus Floor Angle (degrees)	Longitudinal Component (pounds)	Vertical Component (pounds)
0	2500.0	0.0
5	2490.5	217.9
10	2462.0	434.1
15	2414.8	647.1
20	2349.2	855.1
25	2265.8	1056.6
30	2165.1	1250.0

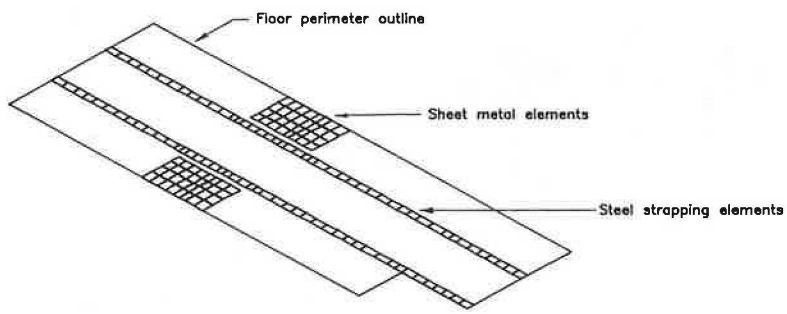

FIGURE 6 Steel strapping and sheet metal elements.

tern used to represent the bus with seat belts consisted of 2,500-lb forces applied to all nodes representing the CG of each passenger as shown in Figure 4. For the bus without seat belts, it was assumed that the forces of the unbelted passengers would be applied to the seat in front of each passenger. Thus, as shown in Figure 7, no forces were applied to the rear seats, 2,500-lb forces were applied to the nodes representing the CG of each passenger for the intermediate seats, and 5,000-lb forces were applied to the nodes representing the CG of each passenger for the front seats.

ANALYSIS RESULTS

The maximum stresses calculated for each element type due to the inertia generated by the bus passengers are given in Table 2 for the bus models with and without seat belts. The floor angles at which the maximum stresses are reached are also given. The longitudinal locations given in Table 2 are measured along the centerline of the bus model beginning at the rear and are normalized with respect to the length of the model. Thus the longitudinal location 0.000 refers to the rear of the model, where the rear bumper would be attached, whereas the longitudinal location 1.000 refers to the front of the model, where longitudinal and vertical pin connections represent the front bumper. The lateral locations given in Table 2 are measured from the centerline of the bus and are normalized with respect to the half-width of the bus. Thus the lateral location −1.000 refers to the left edge of the bus floor, and the lateral location +1.000 refers to the right edge of the bus floor, assuming the reader is facing the front of the bus. For each member type, the maximum and minimum differential member stress to bus deceleration ratios given in Table 3 represent the extreme values derived by calculating the largest and smallest differential member stresses generated for each load case (bus floor angle) for the model with seat belts versus the model without seat belts and then dividing these differential stresses by the 20-*g* bus deceleration. The corresponding floor angles are also given in Table 3.

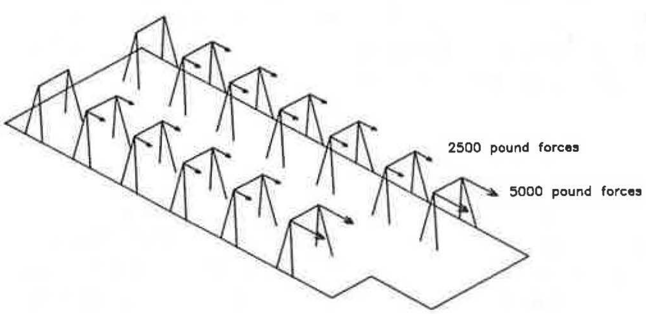

FIGURE 7 Passenger seats and load application for bus without seat belts.

Plywood Floor Elements

The maximum element stresses for the plywood floor elements versus the angle of the floor at maximum bus deceleration are plotted in Figure 8 for the bus with seat belts and for the bus without seat belts. The maximum stresses represent the principal compressive stresses in the plywood floor. The peak stress for the bus without seat belts is 20 percent higher than the peak value for the bus with seat belts. The peak stresses for both bus versions occur near the front passenger seat on the left side, and both occur with a floor angle of 0 degrees. For the bus with seat belts, the maximum stresses are essentially constant versus floor angle, whereas the maximum stresses decrease sharply with increasing floor angle for the bus without seat belts. The reason for the latter is probably a combination of the doubled loads on the front seats of the

TABLE 2 MAXIMUM MEMBER STRESSES AND CORRESPONDING ANGLE OF LOAD AND LOCATION

Description of Member	Model With or Without Seat Belts	Maximum Stress, ksi	Floor Angle, degrees	Location of Maximum Stress	
				Longitudinal	Lateral
Plywood Floor Elements	With	1.5	0	0.837	− 0.418
	Without	1.8	0	0.837	− 0.418
Steel Plate Elements	With	16.1	30	0.300	− 0.418
	Without	19.5	0	0.300	− 0.418
Lateral Frame Elements	With	31.0	0	0.746	− 0.472
	Without	58.2	0	0.746	− 0.472
Perimeter Frame Elements	With	62.0	0	0.194	+ 1.000
	Without	103.8	15	0.681	− 1.000
Skirting Elements	With	29.5	5	0.754	− 0.979
	Without	58.0	0	0.714	− 0.959
Longitudinal Chassis Elements	With	36.8	30	0.288	+ 0.368
	Without	29.0	30	0.577	− 0.368
Longitudinal Channel Cap Elements	With	23.9	30	0.259	+ 0.418
	Without	17.4	30	0.404	− 0.418

TABLE 3 MEMBER STRESS COMPARISONS FOR THE BUS WITH SEAT BELTS VERSUS THE BUS WITHOUT SEAT BELTS

Description of Member	Differential Member Stress to Bus Deceleration Ratios			
	Maximum Value, ksi/g	Floor Angle, degrees	Minimum Value, ksi/g	Floor Angle, degrees
Plywood Floor Elements	+ 0.03	30	- 0.02	0
Steel Plate Elements	+ 0.31	30	- 0.19	0
Lateral Frame Elements	- 0.50	30	- 1.35	0
Perimeter Frame Elements	- 1.90	0	- 2.30	30
Skirting Elements	- 1.15	30	- 1.40	0
Longitudinal Chassis Elements	+ 0.63	15	+ 0.28	0
Longitudinal Channel Cap Elements	+ 0.40	20	+ 0.16	0

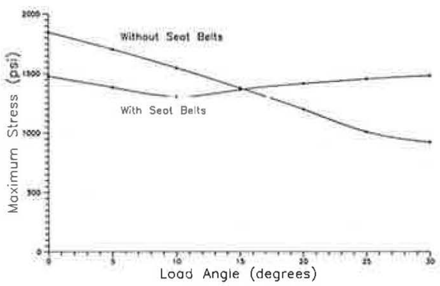

FIGURE 8 Maximum stresses for plywood floor elements.

bus without seat belts and the change in the longitudinal component of the applied loads. The maximum stresses in the bus with seat belts exceeds the maximum stresses in the bus without seat belts at floor angles above 15 degrees.

Steel Plate Elements

For the steel strapping and sheet metal elements, the maximum stresses versus the floor angle of the bus at maximum deceleration are plotted in Figure 9 for the bus versions with and without seat belts. For the bus without seat belts, the peak stress is 21 percent higher than the peak stress with seat belts. The peak stress for the former occurs at an angle of 0 degrees and declines sharply with increasing load angle. The peak stress for the latter occurs at an angle of 30 degrees and is essentially constant. The peak stresses for both bus versions occur near the seats located over the rear wheel wells. This is probably due to the discontinuity of the perimeter and skirting elements along the wheel wells, which tends to concentrate the longitudinal compressive stresses in the floor elements in this region. The relative changes in the maximum stresses for the steel strapping and sheet metal elements versus the angle of the bus floor at maximum deceleration are virtually the same as the changes in maximum stress versus floor angle for the plywood floor elements.

Lateral Frame Elements

Figure 10 shows plots of the maximum element stresses for the lateral frame elements versus the angle of the bus floor for each bus version. The peak stress for the bus without seat belts is 88 percent higher than that for the bus with seat belts. This is probably a result of the doubled loads on the front passenger seats of the bus without seat belts. The peak stresses for both bus versions occur near the front passenger seat on the left side, and both occur with a floor angle of 0 degrees. For the bus with seat belts, the maximum stresses are essentially constant. For the bus without seat belts, the maximum stresses decrease slightly with increasing floor angle. The decrease is probably due to the changes in the longitudinal components of the applied loads.

Perimeter Frame Elements

The maximum stresses for the perimeter frame elements versus the angle of the bus floor are plotted in Figure 11 for the

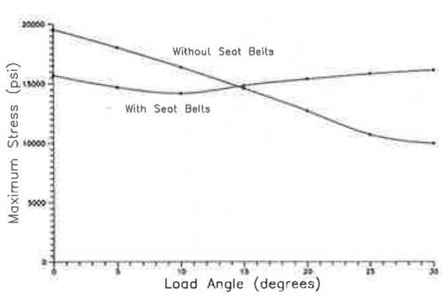

FIGURE 9 Maximum stresses for steel strapping and sheet metal elements.

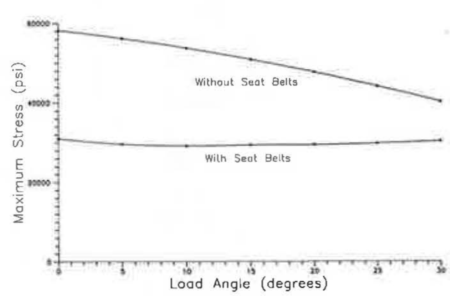

FIGURE 10 Maximum stresses for lateral frame elements.

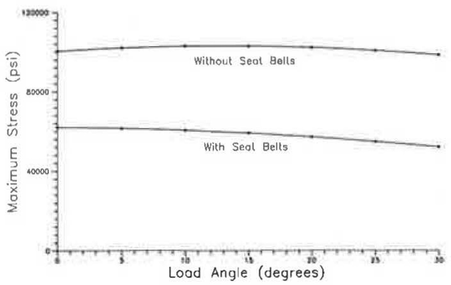

FIGURE 11 Maximum stresses for perimeter frame elements.

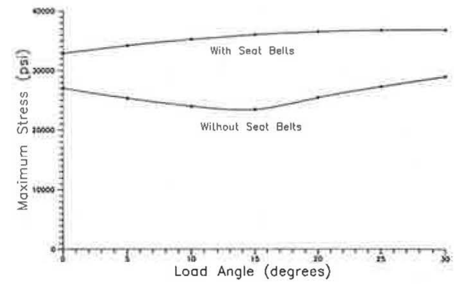

FIGURE 13 Maximum stresses for longitudinal chassis elements.

bus versions with and without seat belts. The peak stress for the bus without seat belts is 67 percent larger than the peak stress with seat belts. For the bus with seat belts, the peak stress occurs along the right side of the bus near the rear wheel wells. The peak stress for the bus without seat belts occurs near the left front seat. For both bus versions, the maximum stresses are essentially constant versus the angle of the bus floor. The peak stresses occur at a floor angle of 0 degrees for the bus with seat belts and at 15 degrees for the bus without seat belts.

Skirting Elements

For the skirting elements, the maximum stresses versus the floor angle at maximum bus deceleration are plotted in Figure 12 for the two bus versions. For the bus without seat belts, the peak stress is 97 percent higher than the peak value for the bus with seat belts. The peak stresses for both bus versions occur along the left side of the bus near the front seat, and both occur at a floor angle of 0 degrees. The maximum stresses are essentially constant versus the floor angle for both bus versions.

Longitudinal Chassis Elements

Figure 13 shows plots of the maximum element stresses for the longitudinal chassis elements versus the angle of the floor for the bus versions with and without seat belts. For the bus with seat belts, the peak stress is 27 percent higher than that for the bus without seat belts. The likely reasons for this difference are the vertical load components that are applied to the rear seats of the bus with seat belts. These vertical loads increase the bending stresses in the longitudinal chassis elements. The peak stresses for both bus versions occur with a floor angle of 30 degrees. For the bus with seat belts, the peak stress occurs on the right side near the rear wheel well. The peak stress occurs near the left front seat for the bus without seat belts. The maximum stresses increase slightly with increasing floor angle for the bus with seat belts and alternately decrease and increase for the bus without seat belts.

Longitudinal Channel Cap Elements

The maximum stresses for the longitudinal channel cap elements versus the bus floor angle are plotted in Figure 14 for the two bus versions. The peak stress for the bus with seat belts is 37 percent greater than the peak stress without seat belts. The reasons for the difference in the peak stresses and the changes in maximum stress versus floor angle are essentially the same as those discussed previously for the longitudinal chassis elements.

SUMMARY AND CONCLUSIONS

A finite element computer model was developed for the structure of a typical transit bus. Assumptions were made about the loading conditions of the bus in the event of a rapid deceleration of the bus. Parametric results for floor angles of 0 to 30 degrees at maximum bus deceleration were derived for bus loading patterns representing the cases with and without seat belts.

The results indicate that the lateral frame members, the perimeter frame members, and the skirting members could

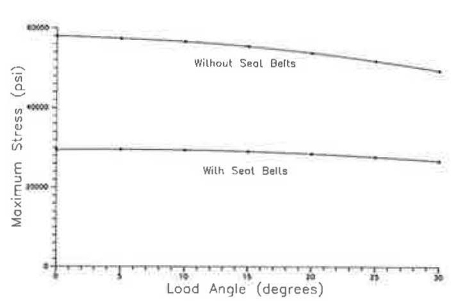

FIGURE 12 Maximum stresses for skirting elements.

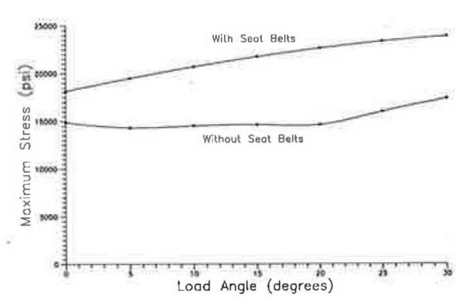

FIGURE 14 Maximum stresses for longitudinal channel cap elements.

all experience moderate to substantial decreases in maximum member stress of -0.50 to -2.30 ksi/g if seat belts are installed on all seats. The plywood floor members and the steel plate members could experience small decreases of -0.02 and -0.19 ksi/g, respectively, to small increases of $+0.03$ and $+0.31$ ksi/g, respectively, in maximum member stress if seat belts are installed. The longitudinal chassis members and the longitudinal channel cap members, which represent the backbone of the bus chassis, could experience moderate increases in maximum member stress of $+0.63$ and $+0.40$ ksi/g, respectively, if seat belts are installed. Thus the presence and presumed use of seat belts on all passenger seats in the event of a rapid bus deceleration should moderately to substantially benefit the frame members of a typical transit bus, whereas the absence of seat belts should moderately benefit the chassis members.

These concluding remarks pertain to the question of the integrity of the structure for a typical transit bus as it relates to the presence or absence of seat belts. A comprehensive literature review conducted as part of the project from which this paper was developed (not reported in this paper) indicates that researchers are divided in their opinions on the overall effectiveness of seat belts on transit buses in reducing severity of injuries. This question is beyond the scope of the present paper.

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REFERENCES

1. D. M. Severy, H. M. Brink, and J. D. Baird. School Bus Passenger Protection. *Automotive Engineering Congress*. Society of Automotive Engineers, Detroit, Mich., 1967, pp. 290–379.
2. D. J. LaBelle. Barrier Collision and Related Impact Sled Tests on Buses in Intercity Service. *Proceedings of the Seventh Stapp Car Crash Conference*. Institute of Transportation and Traffic Engineering, Charles C. Thomas Publisher, Springfield, Ill., 1965, pp. 46–53.
3. K. Rompe and H. J. Kruger. Possibilities of Development in Bus Safety. *International Journal of Vehicle Design—The Journal of Vehicle Engineering Components*, Vol. 7, No. 5/6, Sept. 1986, pp. 178–191.
4. C. R. Ursell. *A Study Relating to Seat Belts for Use in Buses*. Report HS-802 253. U.S. Department of Transportation, 1977.
5. G. N. Farr. *School Bus Safety Study*, Vol. 1. Report TP 6222 E. Traffic Safety Standards and Research, Transport Canada, Ottawa, Ontario, Canada, 1985.
6. D. A. Alianello and W. E. Levan. *Crash Testing of Thomas Minotour Vehicle, 1986 Thomas Bus, Intermediate School Bus*. Calspan Report 7481-1. Calspan Corporation, Buffalo, N.Y., 1986.
7. F. G. J. Van Asperen and H. J. M. Voets. Optimization of the Dynamic Behavior of a City Bus Structure. *Proceedings of the International Conference on the Bus '86*. The Institution of Mechanical Engineers, Mechanical Engineering Publications, Ltd., London, England, 1986.
8. Motor Vehicle Safety Standard 222: School Bus Seating and Crash Protection. *Federal Motor Vehicle Safety Standards and Regulations*. National Highway Traffic Safety Administration, U.S. Department of Transportation, Jan. 28, 1976.

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