FLORIDA STANDARD FOR CRASHWORTHINESS AND SAFETY EVALUATION OF PARATRANSIT BUSES

Cezary, Bojanowski
Jerry, Wekezer
FAMU-FSU College of Engineering, Civil and Environmental Department
United States
Leslaw, Kwasniewski
Warsaw University of Technology, Civil Engineering Department
Jerzy, Kownacki
Motor Transport Institute, Vehicle Type-Approval and Testing Department
Poland
Paper Number 09-0261

ABSTRACT

Research efforts on crashworthiness and safety assessment of paratransit buses were initiated and subsequently supported by the Florida Department of Transportation over the past ten years. They gradually evolved from computational mechanics feasibility studies using non-linear finite element (FE) methods to an industry standard implemented in the state of Florida in August 2007. Paratransit buses sold in Florida can now be evaluated for safety per the state standard based on either experimental testing or on rigorous computational mechanics analysis with validated FE models. Verification and validation (V&V) process is based on multi-scale laboratory testing including: material characterization, wall panel and connection tests, and testing of the entire bus. Validated FE models are subsequently used to provide a comprehensive safety assessment of the entire vehicle.

Two accident scenarios, identified as critical and dangerous by bus manufacturers and operators in the United States, are rollovers and side impacts. Rollover assessment for paratransit buses is based on a tilt table test. It was adopted for the Florida Standard from the UN-ECE Regulation 66 (R66) [1]. In addition, a side impact evaluation was introduced due to a significant segment of large SUVs and pickup trucks among all vehicles sold in the US. Penetration of the residual space is used as a failure criterion in both tests.

The computational track of the assessment program supported by the laboratory validation experiments is presented in the paper. A new method of safety margin assessment in the rollover test based on angular deformations of the bus cross section is introduced. The program has been well received and is now partially supported by the bus industry.

INTRODUCTION

Paratransit buses are defined as small buses that have a maximum capacity of 22 passengers. Production and use of paratransit buses has increased dramatically after 1990 since the Americans with Disabilities Act (ADA) [2] was introduced. The Act defines paratransit buses through their function as a complementary service for regularly scheduled routes. According to ADA - paratransit buses shall be able to transport at least two disabled passengers in their wheelchairs with the use of lifts to assist with the loading and unloading of disabled passengers. In addition to their smaller passenger capacity and different functions compared to a typical bus, paratransit buses also vary in their structure and construction methods. Unlike the monolithic construction of a larger bus, a paratransit bus is built in two distinct stages. First, the chassis and driver cab are produced by a major U.S. automotive manufacturer, most commonly: Ford or GM. In the second stage, smaller companies (called body builders) construct and attach a complete passenger compartment (including all necessary interior equipment) to the chassis.

The Federal Motor Vehicle Safety Standards (FMVSS) define a bus as a motor vehicle with motive power, except a trailer, designed for carrying more than 10 passengers. The separate group standardized by FMVSS code pertains to the school buses. FMVSS does not recognize paratransit buses as a special group of vehicles. Per FMVSS a bus can be either a school bus or “other type of bus” and there is no exceptional treatment of paratransit buses by the standards [3]. The review of national and worldwide standards indicates that paratransit buses with their Gross Vehicle Weight (GVW) often exceeding 10,000 lb and specific way of two-step assembly process make them unique in the existing crashworthiness related regulations. Among US standards, the FMVSS 208 [4] is the only code which provides specific requirements that can be applied exclusively to driver's seat in the bus. At the same time production of passenger cars and school buses is strictly guided by several FMVSS standards and other Regulations: [5], [6], [7], [4], [8]. As a result, elderly and disabled passengers of paratransit buses, who need protection the most, are exposed to greater peril than passengers of other types of vehicles.

The Fatality Analysis Reporting System (FARS) developed by the National Highway Traffic Safety Administration (NHTSA) also does not distinguish a separate group of paratransit buses and places them in the group of "other buses". For that reason, detailed accident statistics regarding the performance of paratransit buses are scarce due to their common inclusion within a more general bus category in overall crash statistics. The communication with the Florida Department of Transportation (FDOT) representatives reveals that paratransit bus accidents do not happen too often. The FDOT indicates however, that the structural strength of paratransit buses is unpredictable and scattered due to different construction techniques and configurations used for the bus body structure. Structure of buses produced by the same manufacturer can differ from one another depending on the modifications required by local bus operators. Such modifications are rarely examined due to the high cost of experimental tests. Yet, the purchase of the new buses must be guided by both safety and economical reasons.

Figure 1. An example of a severe side impact accident between a mid size passenger car and a paratransit bus in Orange County, California (Courtesy: Orange County Register).

Figure 1 shows an illustration of a side impact accident involving a paratransit bus and a mid-size passenger vehicle. The fiberglass-based bus body was barely reinforced by the steel structure and turned out to be a very weak design solution in the impacted bus. As a result, the impact caused a disproportional damage to the bus.

Due to growing size of a paratransit fleet, the FDOT expressed its desire to increase passive safety for Florida paratransit buses in these types of accidents (side impact and rollover). The FDOT requested and sponsored the development of a new methodology that could be used for the bus testing and approval purposes. The main objective of the testing procedure was to indicate which buses are evidently weaker and more susceptible to excessive damage during the impacts. A multilevel research conducted under the FDOT sponsorship resulted in introduction of the crashworthiness assessment program [9] developed by the Crashworthiness and Impact Analysis Laboratory (CIAL). The program utilizes the experiences from computational mechanics studies, expertise of the FDOT, input from industry, and present and past regulations and standards.

This paper is a continuation of the work presented earlier at the EVS Conference in 2007, [10]. Ongoing research performed by CIAL resulted in the enhancement of the V&V procedures for bus rollover simulations, further development of the testing facility for rollover test approval, and in the development of new FE bus models. Multiple computational mechanics analyses and experimental tests performed by the CIAL and the FDOT resulted in valuable findings in the bus rollover safety research. The new safety lever rating system is presented in the paper as an outcome of the performed work.

CRASH AND SAFETY TESTING STANDARD

The Crash and Safety Testing Standard was initially described in the [9]. The complete standard [11] became a part of a former Florida Vehicle Procurement Program (FVPP), which has been recently transformed into the Transit-Research-Inspection-Procurement Services (TRIPS) Program [12]. The main goal of the standard is to assess the crashworthiness and safety of a paratransit bus either by experimental full-scale crash tests, or by the computational analysis using a FE method. At the first step both methods are considered equivalent and either one may be selected by the bus manufacturer for the bus approval.
If the computational method is chosen first and the result of the evaluation is negative, the evaluation can be repeated using the experimental method for the final approval.

The computational mechanics approval procedure is not necessarily the easier one but definitely more affordable for local companies producing paratransit buses. The computational analysis using the FE method requires a reliable and validated FE model. Testing and validation is an additional and necessary step in the numerical approach. The validity is assured thorough comparison of results from specially designed experimental tests with results from the FE simulations (refer to Figure 4 for details regarding validation procedure). The validated FE model is used to assess the crashworthiness and safety of the bus through: a side impact simulation and a rollover test simulation.

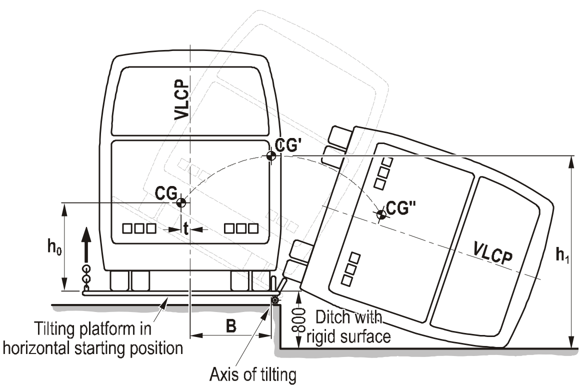

Figure 2. Rollover test setup according to ECE R66 [1].

In the rollover test a vehicle resting on a tilting platform is first quasi-statically rotated onto a weaker side. When the center of gravity reaches the highest, critical point, the rotation of the table is ceased and gravitation causes a free falling off the bus onto the ditch. Concrete flooring of the ditch is placed 800 mm beneath the tilt table horizontal position. Figure 2 shows three relevant positions in the rollover test: initial, critical and just before the contact with the ground.

A paratransit bus is considered to be crashworthy and safe if its residual space (see [1] and Figure 17 for the definition) is not compromised through either intrusion or projection during either actual or simulated tests [9], [1]. Passing results from both: side impact and rollover tests are required for an approval. Moreover, the experimental full-scale crash test is mandatory for further approval if the paratransit bus fails either of the computational analysis tests.

FE MODEL DEVELOPMENT

The FE model was developed for the LS-DYNA simulations [13]. The whole process was in the agreement with the Annex (number 9) to the R66 [1]. The document provided general rules for FE model development, requirements for software used for the approval and type of the results that shall be included in the report from the simulation.

The considered here FE model of a bus was developed in two distinct stages. During the first one, the FE model of the cutaway chassis was extracted from the public domain FE model of the Ford Econoline Van, developed by the National Crash Analysis Center (NCAC) at George Washington University [14]. Computer program LS-PrePost was used to delete redundant Econoline Van parts and LS-DYNA keyword definitions. Subsequently, various geometry modifications were applied to the FE model to convert the chassis from the van (E-150 equivalent) to the heavy duty E-450, based on the specifications used for the tested bus.

In the second stage three-dimensional AutoCAD model of the passenger compartment was built, based on the centerline dimensions of the profiles. Then the frame was translated to IGES (Initial Graphics Exchange Specification) format and imported to HyperMesh preprocessor to create FE mesh and other FE features. Subsequently skin surfaces and relevant elements of interior were developed and attached to the frame. All structural and some nonstructural components of the interior were included in the model to fully replicate mass distribution and inertia properties of the bus. Figure 3 shows the complete FE model of the bus-1 with the highlighted structural members of the body frame.

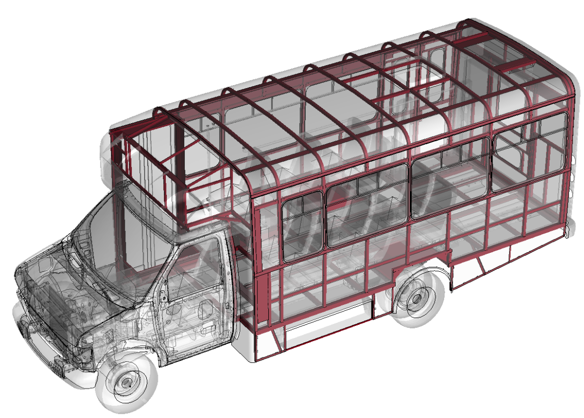

Figure 3. FE model of the bus-1 with highlighted structural members of the bus body.

All members of the frame were connected into one structure using 1-D SPOTWELD elements. The FE model development resulted in over 620,000 finite elements in the base model. Table 1 provides basic information about the bus FE model.

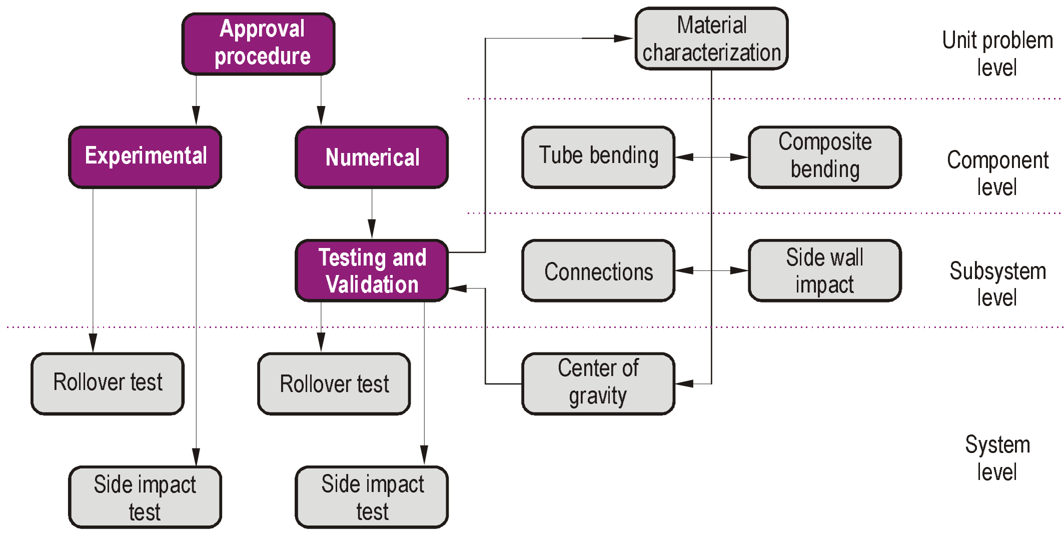

Figure 4. Approval procedure flowchart.

Table 1.
Finite Element model summary

Specification	Count	Specification	Count
elements	623,817	spotwelds	14,284
nodes	661,901	2-d elements	582,467
parts	349	3-d elements	41,342
1-d elements	8	-	-

The model is primarily built from shell elements. Thus, they determine the accuracy and the robustness of the solution. Type 2 shell elements are used as default in LS-DYNA and are frequently used in crashworthiness simulations. This under-integrated element requires about 2.5 times less CPU time than the other common element – type 16. The drawback of the element formulation 2 lays in possible development of nonphysical forms of deformations that produce zero strain and no stress – a process called hourglassing. The rollover simulation is considered to be long lasting (approximately 3 sec.) in comparison to the frontal or side impacts (about 0.2 sec). For that reason the model development process needs special precautions assuring stability of the solution.

The fully integrated type 16 shell element provides the most stable results with low level of spurious energies in the overall response. Thus it was used for the majority of the parts in the FE model of the bus.

The AUTOMATIC_SINGLE_SURFACE contact definition is recommended for crashworthiness simulations [15]. Although it is computationally expensive, it is also easy to implement for the complex models where multiple parts may interact (including self contact) during the simulation.

The concrete pad was modeled by RIGIDWALL option entry in the LS-DYNA. All elements from the bus were defined to be in the contact with that RIGIDWALL. The important parameter of the concrete pad in the rollover test is the friction coefficient between bus skin and concrete. From the experimentally determined range 0.57 to 0.7 [16] the most conservative was assumed – 0.7.

The initial simulations were starting at the unstable position of the bus. The bus was rotated so the CG was slightly beyond the vertical line drawn from the point of the bus rotation to enforce falling from the supporting table. Once the FE model was verified, subsequent simulations were starting with the FE bus model positioned just above the ground (to decrease the CPU time) and proper initial velocities were applied to the bus to reflect original conditions.

FE MODEL VERIFICATION

Introduced in 2006 the American Society of Mechanical Engineers (ASME) standard, titled "Guide for Certification and Validation in Computational Solid Mechanics" [17], defines verification as a process determining that computational model accurately represents the underlying mathematical model and its solution [17], [18]. In other words verification answers the question if equations are solved correctly [19]. Verification process is usually split into two independent parts – code verification and calculation verification. Verification of the code develops a confidence that solution algorithms are working correctly.

Calculation, solution or model verification builds the confidence that the solution of the mathematical model is accurate. It is the analyst's responsibility to perform this part of the verification where the major task is to estimate the amount of a numerical error [17]. Numerical solution error in FE simulations is mainly attributable to the discretization approximation. However, there are other multiple factors influencing correctness and stability of the solution. These quantities can be checked based on the energy balance during the whole process (see Figure 5). During the whole rollover all components defining the total energy should satisfy the principle of energy conservation. Obtained values of energy should also be verified against hand calculations as a first check of the simulation.

Based on the detailed description of the rollover kinematics in [20] an energy balance diagram was created as presented in Figure 5. The time instances marked in the diagram denote:

- t_1 – cantrail collision with the ground and development of plastic hinges in the bus cross sections,
- t_2 – waistrail collision with the ground,
- t_3 – critical structural deformations, plastic hinges stop working,
- t_4 – structural deformations end and elastic deformations are partially recovered,
- t_5 – end of the process.

The total energy applied to the structure during the impact is approximately equal to [1]:

$$E_T = 0.75 Mg\Delta h \qquad (1a).$$

Where:
M – is the total mass of the bus. In the considered case, after inclusion mass of 13 passengers, it was equal to 5.2762 tons.
g – is the acceleration due to gravity and
Δh – is the vertical distance from the highest, unstable position of the bus CG to its final location (In this case it was equal to 1246.3 mm).
Thus the total energy applied to the bus is equal to:

$$E_T = 0.75 \cdot 5.2762 \cdot 9810 \cdot 1246.3 = 48.381 kJ \qquad (1b).$$

The remaining 25 % of the potential energy is dissipated mostly to the ground and through damped vibrations [9]. In the investigated case, the numerically determined value of rigidwall (ground) energy was 18.083 kJ accounting for 28.03 % of the total energy. The maximum value of hourglass energy was 1.081 kJ, or 1.7 % of the total energy. The sliding energy was equal to 2.594 kJ, or 4.09 % of the total energy. The zero level of the potential energy was chosen to be at the final position of the CG. In the graph the energy falls below zero reference level, meaning that the CG of the bus at some point in the simulation is below its final position. It is due to the elastic rebound of the bus.

The energy balance and the grid convergence check should be the two major tasks performed in the verification of the FE model. The grid convergence study is difficult for such big models since subdivision of the elements would result in their overall number greater than 1 million. This check should be performed on the smaller, yet relevant components of the bus.

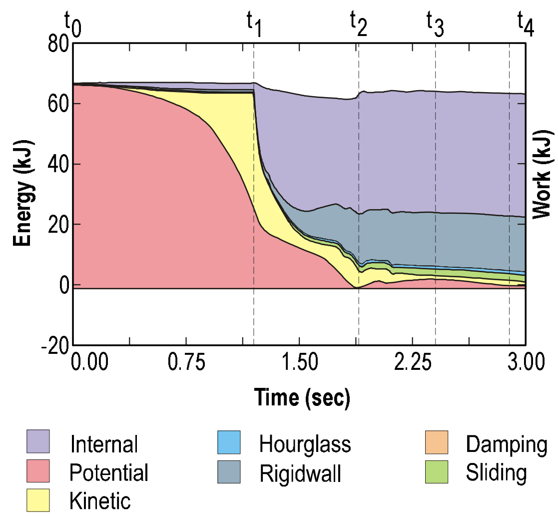

Figure 5. Energy balance for second rollover run transformed to other form.

FE MODEL VALIDATION

Roache, a pioneer of the V&V techniques, [21], describes the difference between verification and validation in his statement: "verification deals with mathematics whereas validation deals with physics". In simple words validation tells if we have chosen correct algorithms to solve our problem [19]. Technically the validation has the goal of assessing the predictive capability of the model for a given simulated event [17], [18]. It is performed by comparison of predicted results from FE simulations to experimental results from the same physical test. It is essential to select validation tests that are closely related to the event for which model is intended.

As advocated by the ASME standard "Guide for Verification and Validation in Computational Solid Mechanics" [18], the validation experiments of complex systems should have hierarchical character. Several tests were chosen as the most relevant for the bus structure and rollover test considered. Material characterization is at the lowest level of the validation hierarchy. Bending of steel tubes and skin composite samples can be categorized as testing at the component level. The bending of the connections and impact test on the side wall panels can be considered as tests on the subsystems of the structure. At the complete system level, a center of gravity (CG) check shall be performed. The proposed tests comprise only the required minimum that provide information about the behavior of the main structural components. Depending on time and budget constraints, additional tests shall be conducted for better results and increased model reliability. The most desirable then would be the testing of connectors (adhesive, welds and bolts).

Bending of Structural Tubes

Three buses were investigated in this research project. They are coded as bus-1 to bus-3. However, the numerical results are presented for the bus-1 exclusively.

The main structural elements in the considered paratransit buses are usually build from square tubes. Their dimensions and results from the steel tension testing for all three buses are shown in Table 2. According to [22] (Table B4.1) for uniformly compressed flanges of rectangular box and hollow structural sections subject to bending, the limiting ratios for compact and noncompact profiles respectively are calculated using the formulas:

$$\lambda_p = 1.12\sqrt{\frac{E}{\sigma_y}} \qquad \lambda_r = 1.40\sqrt{\frac{E}{\sigma_y}} \qquad (2).$$

The HSS 1.5 in x 1.5 in x 18 ga tubes, used in the bus-1, are in the intermediate level and two other cross sections are in the compact regions.

A four point bending test was selected as the direct measure of the strength of the tubes and the validation of the model. The testing apparatus for the four point bending is shown in Figure 6. The distance between the external (moveable) supports is equal to 900mm and 300 mm between internal supports. The internal supports were connected to the grip through the hinge.
The diameter of supports was equal to 30 mm.
The INSTRON 8802 testing machine with FastTrack software was used for the tests. The displacement was applied with the rate of 20 mm/min. The bridge tensometer ESAM Traveller PLUS was used for the test together with the LVDT's RC20-100-G [23]. The displacement of the bottom (moveable) traverse is denoted as d_0. Additionally deflection of the beam in points d_1 and d_3 (under the internal supports) and d_2 (middle of the beam) were recorded.

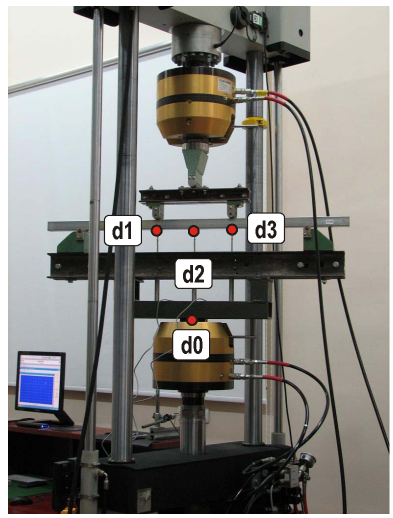

Figure 6. Testing apparatus for four point bending test.

The quantitative results of the tests are shown in Figure 7. For HSS 1.5 in x 1.5 in x 18 ga (bus-1) tubes local buckling was the reason of reaching ultimate strength. Although the cross section in the case of HSS 1.5inx1.5inx16ga (bus-1) tubes is compact the local buckling also occurred. In the case of the bus-3 tubes the cross section was considered as compact and with λ low enough the local buckling was not present. Only global deformations were present in this instance as shown at the bottom three specimens in Figure 7.

Figure 7. Deformed tubes as a result of the four point bending tests.

Table 2.
Mechanical properties of tested steel

Steel source	Tubes dimensions	Young's modulus $E(MPa)$	Yield stress $\sigma_y(MPa)$	Ultimate strain $\varepsilon_u(-)$	Cross section classification
bus-1	1.5 in x 1.5 in x 18 ga	171300	281.1	0.36	intermediate
bus-2	1.5 in x 1.5 in x 16 ga	222400	359.0	0.25	compact
bus-3	1.0 in x 1.0 in x 16 ga	207300	389.4	0.18	compact

Figure 8 contains averaged curves presenting the exerted load plotted against the displacement of the point d_0 for three types of tested tubes. Although the 1.5 in x 1.5 in x 18 ga tube used in the bus-1 has a greater cross-sectional area than 1.0 in x 1.0 in x 16 ga, bus-3 tube, the obtained ultimate strength is only 15% greater than the ultimate strength of bus-3 tubes. At the same time it is 75% weaker than 1.5 in x 1.5 in x 16 ga, bus-2 tube.

The same test for the bus-1 was also simulated using the LS-DYNA software. The load – displacement curve from the FE analysis is also shown in Figure 8. The ultimate load obtained in the simulation was 5.012 kN which results in 1.8 % of the relative error when compared with the experimental value of 5.108 kN.

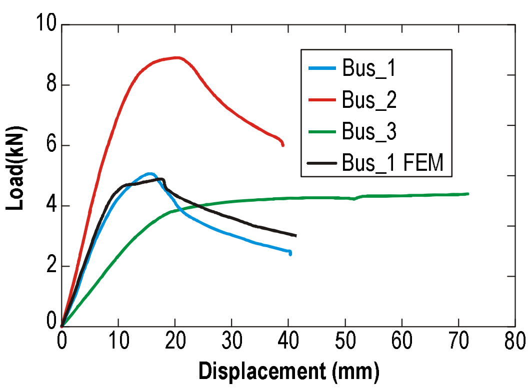

Figure 8. Load-displacement characteristics for tubes tested in bending.

Bending of the Connections

The bus body is constructed by first assembling the major components (floor, sidewalls, backwall, roof) individually and then welding and/or bolting them together. This process creates major connections between the subsections. Dynamic performance of these connections does not only depend on the material properties but even more significantly of the selected connection design which is affected by the bus assembly process.

Figure 9 shows location of the wall-to-floor WF (1) and roof-to-wall RW (2) connections selected for connection testing.

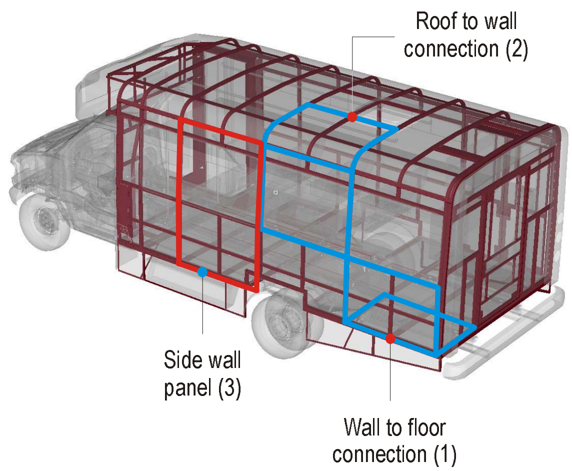

Figure 9. Location of components for connection testing in the bus structure.

Representative samples of the connections were obtained from the manufacturer for the study of the RW and WF connections. Connections are tested in bending where one side is clamped and the other is pulled quasi-statically to decrease the angle between both sides. The testing apparatus shown in Figure 10 was designed to measure the resistance response of the connections.


Figure 10. RW connection without skin fixed for bending testing.

It allowed for data acquisition of a rotation angle of the connection as a function of the force (or: equivalent moment) applied. A large concrete block is used as a base and the lower part of the test section is fixed by butting against this block and then being bolted to the floor through the aluminum I-beams. Two hand winches are attached to either side of the block and connected to the test section with an in-line Strainsert tension link rated at 17,793 N (4,000 lbs) full scale to the load application point. Displacement was measured using two SpaceAge Control D62-60-82E1 wire-type position transducers for each side (North and South), vertically spaced on the concrete block (d_1, d_2, d_3, d_4), but connected to the same point on the test section to provide the vertical and horizontal displacement using triangulation technique. The data recorded included the load and two displacements for each side using a SCXI DAQ data acquisition system and LabVIEW 8.2 software. The load application was quasi-static and keeping the displacement of each side almost equal.

Figure 11 and Figure 12 present characteristic curves obtained for two connections – WF and RW respectively. Together with the experimental results the curves from corresponding LS-DYNA simulations are shown. The FE simulations were conducted for two cases of different tubes thickness – 100 % of nominal and 93 % of nominal thickness, which was equal to the measured thickness of the walls.

In the case of the WF connection the deformation of 18 deg is equivalent to the failure of the bus (in terms of the residual space) in the rollover test. For the simulation of the test with reduced thickness the bending moment reached 446.4 Nm whereas corresponding value in the experiment was equal to 451.4 Nm. The relative error was only 1.1 %.
In the RW connection the angle of the deformation of 39 deg is equivalent to intrusion into the residual space during the rollover test. The value of the bending moment at that deformation level in the experiment was equal to 371.1 Nm. For the FE model with reduced thickness the moment was 351.2 Nm. It resulted in the relative error of 5.3 %.

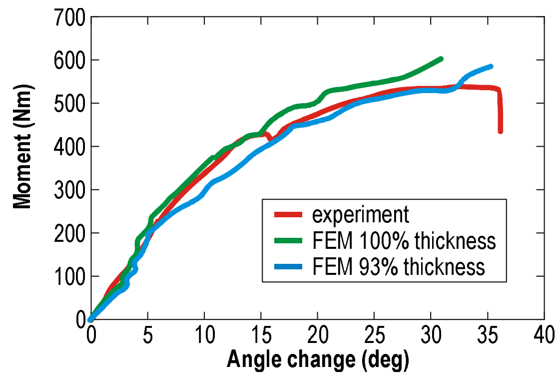

Figure 11. Comparison of results for WF connection without the skin.

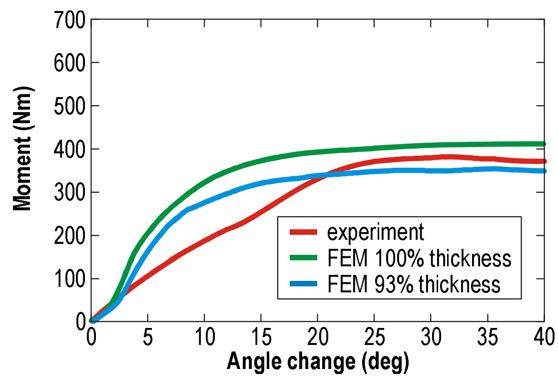

Figure 12. Comparison of results for RW connection without the skin.

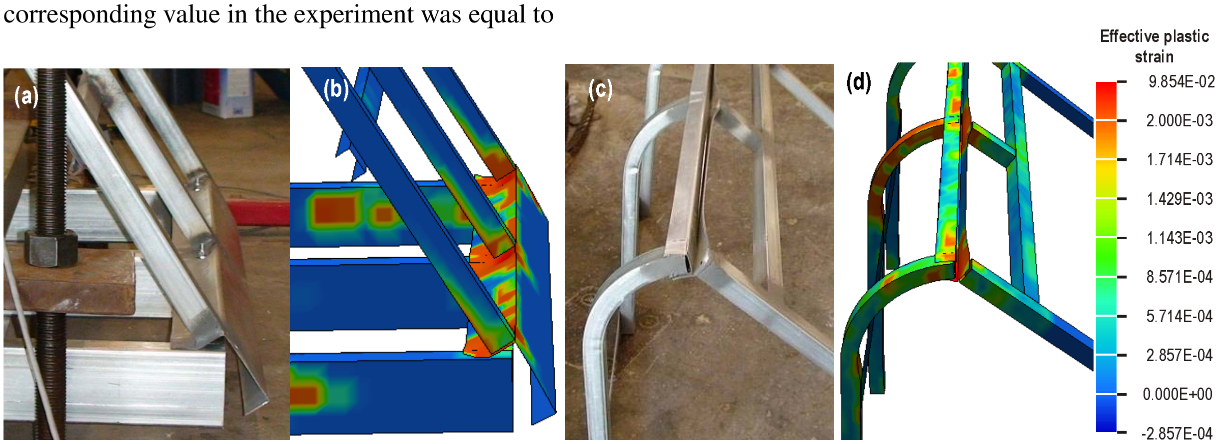

Figure 13. Deformations in the tested skinless connections from bus-1 (a) WF connection (b) FE model of WF connection (c) RW connection (d) FE of RW connection.

Figure 13 shows deformations in the connections obtained in the experiments and corresponding deformations in the FE simulations. The figures reveal poor design of the connections. The major deformations occurred not in the structural beams but in the transition members like C-channel in the WF connection and L-shape in the RW connection. In order to increase the strength, the elements should have additional welds and/or bolts preventing unnecessary and excessive deformation.

Side Wall Impact Test

A dynamic impact test on the side wall panel was developed for additional model validation. Location of the side wall panel used for the testing in the bus structure is shown in Figure 9 under the number 3. The panel is cut off from the wall and extends from the cantrail to the level of the floor. Its width spans two major vertical beams (which are included in the panel) thus both dimensions (height and width) differ for every single bus model. Initial conditions for the test are shown in Figure 14.

The panel is resting horizontally on raised tubular supports with 150 mm diameter. The two supports are at adjustable distance which in this case was 1600 mm. The impacting device is comprised of impacting square tube, perpendicular rectangular arms and crossing rectangular beams. It is mounted to the supporting beams in the way that allows free rotation of the device. All elements are made of steel. The impacting arm is suspended on the steel wire and connected to the hand winch allowing for raising the arm. In the test the hammer is dropped from the pre-calculated height assuring reasonable amount of the deflection imposed by the impact. In this case the initial height was 700 mm. The total mass of the impacting device is 132.4 kg. The location of the impact zone is selected to be below the waistrail level which is close to the middle of the panel. Due to the short duration of the event only the final results of the experiment are captured. The character of deformation and maximum deflection are recorded and then used for comparison with numerical results.

In the design of the side wall used for the test the waistrail beam was continuous throughout the length of the bus and the vertical beams were welded to it at the top and the bottom. Discontinuity of the vertical pillars resulted in the excessive local deformations in the waistrail beam as shown in Figure 15 b. Figure 15 a shows corresponding deformations in the FE simulation for comparison.

The basic model with two finite elements across the beam width was not capable of capturing such severe deformation. The mesh density had to be increased to fully reflect real deformation pattern. With the increased mesh density, obtained deflection in the FE simulation was equal to 298.8 mm. In the experiment the deflection was 312.0 mm which gave the relative error for the FE simulation of 4.2 %. Such design should be avoided in the bus structure since the capacity of it depends only on the strength of the single thin wall of the waistrail beam.

In the research another design was checked where the waistrail beam was discontinuous and was welded to the continuous vertical columns in the wall structure. The design was subjected to the same loading conditions and Figure 15 c shows local deformations in it. The deformation was less dramatic and the overall deflection of the panel in the test was reduced to 81.1 mm. It is equal to 72.8 % reduction of the displacements.

Summary of the V&V program

The FE model of the bus was verified for numerical errors and the instabilities in the solution. The energy balance was used to prove sanity of the calculations and compare obtained values of the total energy, and energy dissipated into the ground, with empirically expected values. The non-physical hourglass energy was shown to stay below 5 % of the total. The same condition applies to the sliding interface energy.

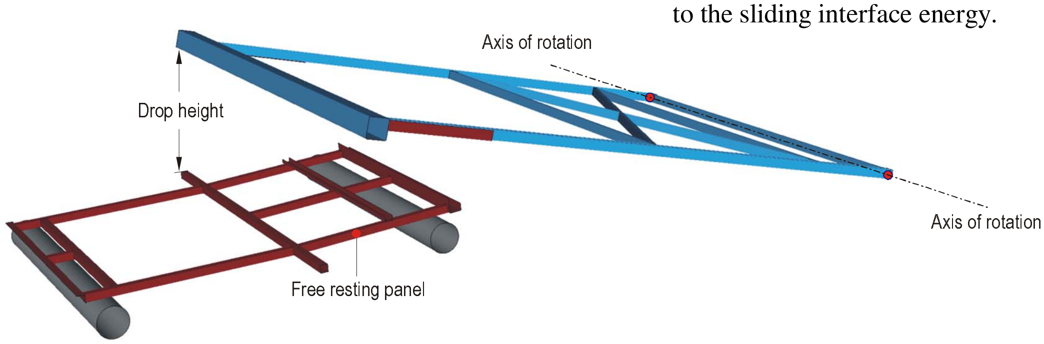

Figure 14. The FE model of the side wall panel without the skin.

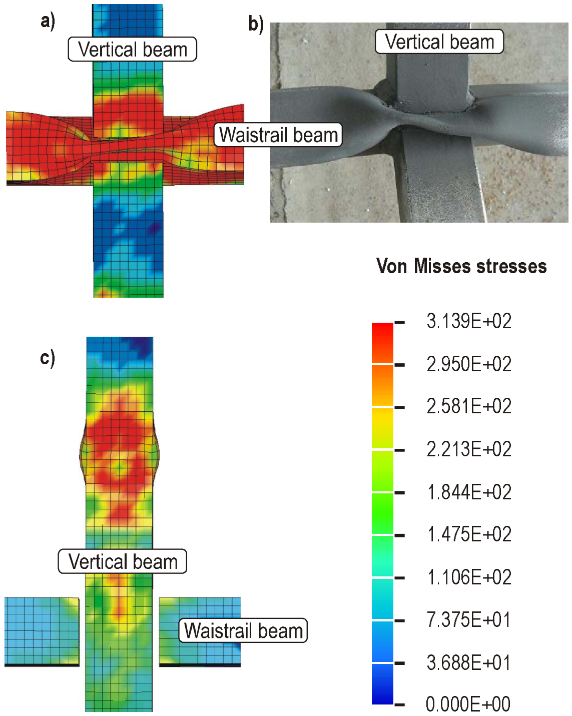

Figure 15. Local deformations in the tested panels.

The number of elements on the edge of the main tube in the entire bus model was increased to 4 after the side wall panel tests. Still it is lower than 8 elements used in the FE simulation of the side wall impact test.

Other factors also contribute substantially to the overall response of the bus in the rollover test. The bonding strength of the adhesive used between the skin and the frame is one of them. Yet, the most crucial, steel cage can be assumed to be fully validated.

SIMULATIONS OF THE ROLLOVER TEST

The verified and validated FE model of the bus was subsequently used in the simulations of the rollover standardized test. A follow up case study was performed on the FE model that answered several theoretical and technical questions regarding the bus rollover. For the purpose of this research a new measure quantifying safety margin in the rollover test was introduced. The current UN-ECE Regulation 66 does not define any quantitative measure to assess extent of the deformation and the safety margin in the rollover test. The pass/fail decision is the only outcome from the test procedure per R66. The proposed deformation index DI_α can be very advantageous for comparative studies in rollover simulations. The common measure of the vehicle response in the accident – intrusion may be hard to interpret in the case of rollover since deformation in actual accidents often includes twisted patterns. Moreover, the width of the residual space varies with the height. Since the cross-section of the bus deforms primarily in several vulnerable spots through plastic hinges (PH), the rest of the structure deforms considerably less. It is more innate to measure the angular deformations at the expected plastic hinges. Figure 16 presents a cross section of the bus with the numbered angles measured at the hypothetical PHs. These are:

- α_1, α_6 – wall to floor connections angles,
- α_2, α_5 – waistrail angles,
- α_3, α_4 – roof to wall connections angles.

These angles are used to measure one deformation index DI_α. This index, together with the pass/fail grade, can provide a more descriptive assessment of the bus structure deformation level in the rollover test. The deformation index DI_α can be defined as a function of two major angles:

$$DI_\alpha = f\left(\Delta\alpha_1, \Delta\alpha_2\right) \qquad (3).$$

Where:
$\Delta\alpha_1, \Delta\alpha_2$ – are the changes in the respective angles due to the rollover impact deformations at the side impacting the ground.

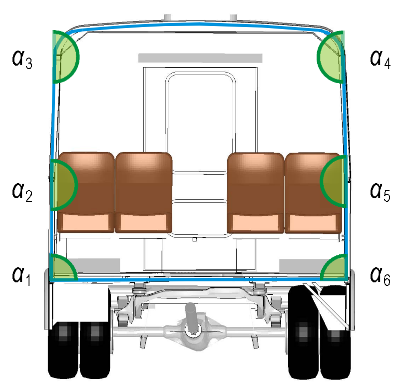

Figure 16. Angles of interest in the bus cross section.

Figure 17 shows the geometry of the bus cross section in an arbitrary failure mode. Deformation angles are combined with the definitions of the residual space to lead to the derivation of the approximate expression for DI_α.

The distances w_1, w_2 from Figure 17 are defined as follows:

$$w_1 = l \cdot \tan(\Delta\alpha_1) \quad (4).$$

$$w_2 = (h - l) \cdot \tan(\Delta\alpha_2) \quad (5).$$

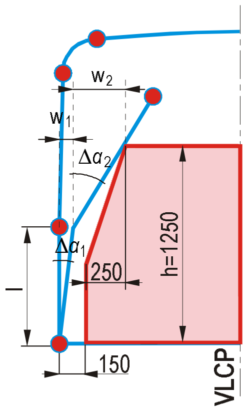

Figure 17. Geometry of the failure mode.

Their sum for the critical state is equal to *d*:

$$w_1 + w_2 = d = 150 + 250 = 400mm \quad (6).$$

Substituting w_1 *and* w_2 from Equations 4 and 5 yields:

$$l \cdot \tan(\Delta\alpha_1) + (h - l) \cdot \tan(\Delta\alpha_2) = d \quad (7).$$

or:

$$\frac{l}{d} \cdot \tan(\Delta\alpha_1) + \frac{(h - l)}{d} \cdot \tan(\Delta\alpha_2) = 1 \quad (8).$$

Thus the deformation index DI_α can be defined as:

$$DI_\alpha = \frac{l}{d} \cdot \tan(\Delta\alpha_1) + \frac{(h - l)}{d} \cdot \tan(\Delta\alpha_2) \quad (9).$$

or with numerical values:

$$DI_\alpha = \frac{l}{400} \cdot \tan(\Delta\alpha_1) + \frac{(1250 - l)}{400} \cdot \tan(\Delta\alpha_2) \quad (10).$$

The formula seem to be complicated at the first glance but in fact only three quantities need to be measured in order to determine the safety level of the bus. Consider three basic cases of failure configuration for a modeled bus with the angle changes given in Table 3. The distance *l* in this case was equal to 788mm. Equation 10 becomes:

$$DI_\alpha = \frac{788}{400} \cdot \tan(\Delta\alpha_1) + \frac{(1250 - 788)}{400} \cdot \tan(\Delta\alpha_2) \quad (11a).$$

$$DI_\alpha = 1.97 \cdot \tan(\Delta\alpha_1) + 1.155 \cdot \tan(\Delta\alpha_2) \quad (11b).$$

Table 3 shows computation of the deformation indices for the three simple failure modes of the bus cross section. It is assumed that the deformations occur only in the PHs and the deformation of the rest of the structure is negligible. It needs to be pointed out that the $\Delta\alpha_2$ in the formula is a sum of the angle changes α_1 and α_2, and the absolute value of angle changes are used in the formula.

Table 3.
Comparison of the deformation index for three simple failure modes of the bus cross section in the rollover test

Specification	*Failure mode I*	*Failure mode II*	*Failure mode III*
α_1	18.0	0	10.0
α_2	0.0	39	19.0
DI_α	1.015	0.935	0.988

DI_α index can be effectively used to assess a safety margin. The structure is considered inacceptable, or it is assigned one rating star, when DI_α is equal or greater than 1. It indicates an intrusion into the residual space and the bus fails the rollover test according to the UN-ECE Regulation 66.
The maximum grade of five stars is assigned to strong structures with 60 % safety margin with the corresponding $DI_\alpha = 0.4$. Other ratings for the DI_α are proposed in Table 4.

Table 4.
Rating ranges for the proposed deformation index DI_α

Range	*Descriptive strength rating*	*Star rating*
$DI_\alpha < 0.4$	strong	*****
$0.4 \le DI_\alpha < 0.6$	intermediate	****
$0.6 \le DI_\alpha < 0.8$	acceptable	***
$0.8 \le DI_\alpha < 1$	poor	**
$DI_\alpha \ge 1$	inacceptable	*

Influence of the Skin Layers

The influence of the skin layers on the bus rollover performance was checked. R66 requires testing the strength of the superstructure in the rollover test. The superstructure is defined as a part of the bus structure that contributes to the bus performance in the rollover test. Often the skin part is ignored in the FE model to simplify the modeling. Although this procedure may seem effective and trustworthy for long buses it appears to be vague for the shorter vehicles. Whenever the thin walled structure (like bus shell) is in torsion then that thin layer of the skin really matters as far as strength is considered.

Figure 18 shows the deformed cross section of the buses with- (a) and with-out (b) the skin on it. In the case (a) the residual space is not compromised. Computed for this case the deformation index was equal to 0.69, what gives the bus "three stars" in the rating system introduced in Table 4. In the case (b) the results are completely different. The residual space is visibly penetrated.

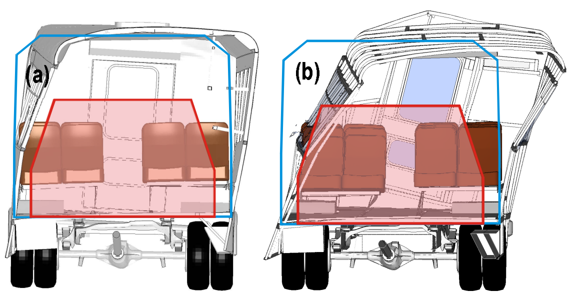

Figure 18. Deformation of the bus body in rollover simulation (a) bus with the skin (b) bus without the skin

Table 5.
Comparison of angular deformations in the models with (model 1) and without the skin (model 2)

angle	initial stage	angle change 1	angle change 2
α_1	90	-11.5	-21.8
α_2	177.6	-2.5	-16.3
α_3	180.0	19.8	34.1
α_4	180.0	-7.9	-41.7
α_5	177.5	-0.2	2.2
α_6	90	7.5	14.8
DI_α	-	0.69	1.31

The angular deformations in the plastic hinges presented in Table 5 differ substantially. The deformation index for the model without the skin is 1.31, meaning, it increased 89.8 %. It becomes obvious that the skin sheets contribute substantially to the rollover resistance of the paratransit buses.

Initial Conditions Sensitivity

Sensitivity of the results due to variations of initial conditions has been checked. The repeatability of the results from a full scale rollover test according to R66 is sometimes questioned by engineering community in the US [24]. FE analysis is an efficient method to check that hypothesis. In the simulation presented previously the bus hits the ground uniformly along the entire cantrail length. Two additional cases were investigated. In the first the bus was rotated 3 deg with respect to its yaw axis in such a way that the front part of the bus is closer to the ground (negative yaw angle) – model "F". This way, the more vulnerable frontal part of the bus will take the first impact. Subsequently, a positive angle of 3 deg was applied and the bus had its first impact to the ground at the the back cantrail corner – model "R". Such apparently negligible disturbance may easily happen in the real world test where many factors (e.g. behavior of the tire during the test) are of a rather unpredictable nature.

Table 6.
Comparison of angular deformations in the models with different initial conditions

angle	initial stage	angle change F	angle change R
α_1	90	-16.1	-13.2
α_2	177.6	-1.1	-1.2
α_3	180.0	20.4	14.2
α_4	180.0	-12.4	-9.0
α_5	177.6	-0.3	-0.3
α_6	90	14.6	6.2
DI_α	-	0.93	0.76

Table 6 shows the values of the angle changes compared for both cases considered. In the first case the DI_α increased from the initial 0.69 (base model) to 0.93 (34.7 %), and in the second case it increased to 0.76 (10.1 %). This study shows that rollover tests are sensitive to variations in the initial conditions. Different structure stiffness of the front and rear end of the paratransit bus may cause significant discrepancies in real tests depending on which part of the bus will touch the ground first.

Influence of the Strain Rate Effect

The question about the importance of strain rate effect in the structural steel for the rollover accidents was raised among the bus rollover testing community too [25].

Additional FE bus model was virtually tested to investigate the strain rate effect on rollover test results. In the modified base model - the strain rate effects were not accounted for (model "NO-CP"). The only difference between the base model and "NO-CP" model is that the *C* and *p* parameters in the Cowper-Symonds strain rate dependency model were turned off. The set of parameters: C=80 and p=4 was used in the base model [14]. No dramatic difference in the response of the bus was noticed in the simulations. Table 7 shows angle changes for these models. Yet, the DI_{α} difference for the models was 7.2 %.

Table 7.
Comparison of angular deformations in the models with different Cowper Symonds parameters and different mesh densities

angle	initial stage	angle change	angle change NO-CP
α_1	90	-11.5	-9.3
α_2	177.6	-2.5	-10.7
α_3	180.0	19.8	17.7
α_4	180.0	-7.9	-10.6
α_5	177.6	-0.3	-0.5
α_6	90	7.5	11.9
DI_{α}	-	0.69	0.74

CONCLUSIONS AND FUTURE WORK

The current status of the research on the Florida standard for crashworthiness and safety evaluation of paratransit buses was presented. Verification and validation methodology for the Finite Element simulations of standardized rollover test are introduced. Computational mechanics analyses were verified by the energy balance tracking and complementary hand calculations. The numerical results were compared to the results from the experiments on different levels of the validation hierarchy. Good correlation of results was obtained for each case. Computer simulations provided answers to several technical questions. In particular it was shown that:

- The bus skin is an essential element of the FE model. It significantly contributes to the overall strength of the bus.
- The rollover test according to R66 [1] may be sensitive to the disturbance of initial conditions depending on the bus structure.
- Negligence of the strain rate effect in the rollover test results in about 7% of the difference in the response of the bus.

Also the deformation index and the star rating system are proposed to assess safety margin in the rollover test.

The first full scale rollover tests on paratransit buses in the state of Florida was performed by CIAL and FDOT in December 2008. It is planned to provide in the future comparative results from these tests along with results from the corresponding numerical simulations.

ACKNOWLEDNGEMENTS

The study reported in this paper was supported by a grant from the Transit Office of the Florida Department of Transportation titled: "*Crashworthiness Assessment of Paratransit Buses*", FSU Project No. 018679, FDOT project BDD 30. Opinions and views expressed in this paper are those of the authors and not necessarily those of the sponsoring agency. The authors would like to express their appreciation for this generous support and wish to acknowledge the assistance and support from Robert Westbrook, the Project Manager, and Erin Schepers. Design and development of a tilt table was partially supported by a grant from the Federal Transit Administration (Pauline D'Antignac – Project Manager). Thanks are due to Paul Johnson, an independent consultant, for his commitment, advice, and technical support during this project.

REFERENCES

[1] United Nations; *Strength of the superstructure of large passenger vehicles. Regulation 66. Revision 1.* http://www.ECE.org/trans/main/wp29/wp29regs/r066r1e.pdf, February 22, 2006, last access date: July 11, 2007.

[2] U.S. Department of Labor, *The Americans with Disabilities Act of 1990*, http://www.dol.gov/esa/regs/statutes/ofccp/ada.htm. August 16, 2006.

[3] *Highway Special Investigation Report, Bus Crashworthiness Issues*. 1999, National Transportation Safety Board: Washington, D.C.

[4] Federal Motor Vehicle Safety Standards and Regulations, US Department of Transportation. FMVSS 208 *Occupant crash protection*, 1973.

[5] Federal Motor Vehicle Safety Standards and Regulations, US Department of Transportation. FMVSS 220 *School bus rollover protection*. 1998

[6] Federal Motor Vehicle Safety Standards and Regulations, US Department of Transportation. FMVSS 216 *Roof crush resistance* 1994.

[7] Federal Motor Vehicle Safety Standards and Regulations, US Department of Transportation. *Roof crush resistance, new proposal*, 2005.

[8] Federal Motor Vehicle Safety Standards and Regulations, US Department of Transportation. *upgrade to FMVSS 216 Roof Crush Resistance*, 2008.

[9] Kwasniewski, L., et al., *Crash and safety assessment program for paratransit buses,* International Journal of Impact Engineering, Volume 36, Issue 2, February 2009, Pages 235-242

[10] Li, H., et al., *Laboratory Testing Program for F.E. Crash Analyses of Paratransit Buses*. 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper No. 07-6539, Pages Li 1 - Li 7 (on a distributed CD). Lyon, France, June 18-21, 2007.

[11] CIAL, *Crash and Safety Testing Standard for Paratransit Buses Acquired by the State of Florida*, FDOT, August 10, 2007. http://www.tripsflorida.org/pdfs/Crash%20and%20Safety%20Testing%20Standard.pdf

[12] FDOT *Transit Research Inspection Procurement Services (TRIPS) Program*. 2009 [cited 2009 March 08, 2009]; http://www.tripsflorida.org/index.html.

[13] Hallquist, J.O., *LS-DYNA Keyword User's Manual*, LSTC, 2007: Livermore, CA.

[14] NCAC, *Finite Element Model Archive*. 2008, http://www.ncac.gwu.edu/vml/models.html.

[15] LSTC, *Modeling guidelines for full vehicle contact*. 2001; http://www.dynasupport.com/support/tutorial/contact.modeling/Full.Vehicle.Contact.

[16] Rabbat B.G., *Friction coefficient of steel on concrete or grout.* Journal of Structural Engineering, 1985. 111(3): p. 505-515.

[17] Schwer, L.E., *An Overview of the ASME Guide for Verification and Validation in Computational Solid Mechanics*, in *LS-DYNA Anwenderforum*. 2006: Ulm.

[18] American Institute of Aeronautics and Astronautics (AIAA), *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*. 1998, Reston, VA.

[19] Oden, J.T., *A posteriori estimation of modeling and approximation error in computational science and engineering: new tools for verification and validation of computer simulations*, in *Fifth World Congress on Computational Mechanics*. 2002.

[20] Matolcsy, M., Molnar, C., *Bus Rollover Test as a Process and its Energy Balance*. in *30th Meeting of Bus and Coach Experts*. 1999. Gyor, Hungary.

[21] Roache, P.J., *Verification and Validation in Computational Science and Engineering*. 1998, Albuquerque, NM: Hermosa Publishers.

[22] American Institute for Steel Construction (AISC), *Steel Construction Manual*. 13th ed, 2005.

[23] P3 America, I. *P3 America, Inc. Precision Sensors & Positioners*. 2006 ; http://www.p3america.com/pp/rc20.htm.

[24] Saul, R.A., *NHTSA's Approach to Motorcoach Safety*. 2007, U.S. Department of Transportation, National Highway Traffic Safety Administration, http://www.trb.org/news/blurb_detail.asp?id=8013

[25] Kwasniewski, L., *Personal conversation with member of Informal Group of Experts for UNECE R.66*, in *IG/R.66*. 2008.