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Testing and Optimization of Bus Skeleton That Contains Thin Walled Tubes In Both Axial Impact And Rollover

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Abstract: *The proposed work represents an evaluation of single-deck bus structure members, which is a rife design for this category of busses that are widely produced and used in Egypt.In fact, structure parts in the front end of a bus body will be subjected to plastic deformation, in case of a frontal collision, which absorbs the major part of the kinetic energy according to structure design characteristics.The safety issue is to achieve the maximum possible absorbed energy with minimum intrusion for front-end.The first objective of the current work is to implement experimental testson four different square sections usually used in such structure to investigate their crash behavior. Moreover, the influence of wall thickness and section width of a square-shaped section of the design parameters are investigated. Furthermore, Response Surface Methodology (RSM) optimization technique had been used to optimize the design parameters of the structure members.The second objective of the current thesis is to evaluate a section of the bus structure behavior during rollover test according to prescribed standard regulation. This evaluation relies on a rollover (FE) Model in addition to an experimental rollover testing procedure carried out on a physical section of the bus. This rollover simulation had been implemented on the selected section of the proposed bus structure in ANSYS (Static Structural Module). Consequently, experimental rollover test had been carried out on the selected bus section to validate the numerical simulation by using a tilting platform.*

Key Word*:Response Surface Methodology (RSM) optimization, Thin walled structure members*

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I. Introduction

The experimental evaluation of bus structural behavior during frontal collision required special Instruments and devices, these tools need very expensive cost, especially if the test is repeated. But now by using simple methods and lower cost and the accuracy approaching practical tests the researchers can be assessments the buses safety [1]. In fact, their use to reduce product development cost and time while improving the safety, comfort and durability of the vehicles they produce by applying the improvements in first on the computer simulation [2]. A collision occurs when the bus and the barrier interact in a short period of time. This causes large force and momentum which typically deforms the bus body. Immediately aftertouch, the compression stage begins where the colliding masses deform and absorb kinetic energy in the structural members. The kinetic energy of the bus body converting to absorbed energy through plastic deformation in the structure members [3]. The first stage of a collision of bus into a fixed barrier as shown in Figure (1), during the bus is just touching the barrier into maximum intrusion. During the rebound stage some of the stored energy is turned back into kinetic energy as the masses depart with some relative velocity [4]. Almost the Skeleton of the space frame consists of square sections, the details of the structure members are essential to predict the crash response, the principles of the structure geometrical such as hollow sections dimensions, wall thickness [5]. Bus rollover accident is one of the most dangers for the safety of occupants in a bus. Must observing the bus body structure after rollover accidents, if the buses structures are Unsecured designed, the consequences will be bad. Hence, threatens the lives of occupants. Rollover strength has become an important issue for bus structure manufacturers. The governments must find a legal way to oblige the manufacturers of passenger buses especially in developing countries to applying the safety requirements according to international standard regulations and recommendations especially during pre-design steps and on the prototype sample to maintain the occupant life and reduce the injuries.Nowadays for the passenger bus manufacturers, we have many local producers which construct buses based on local needs.The current work discusses and implement the rollover test on the proposed design of the bus section according to UNECE (R66) [6].

Figure (1): Bus frontal collision with a fixed barrier and Rollover accidents.

II. Axial Steel TubesDesign Characteristics

The buses carriage more than eight passengers and the driver, with a maximum mass exceeding five tons are classified according to ECE into Category M3.The evaluation of the bus cabin during frontal collision is based on the behavior of the structural components. Also include the structure members arrangement and rails design configuration such as cross-section and wall thickness also are significant factor. Stiffness and energy absorption of a structure element give a hint of performance.To evaluate the structure characteristics of the bus body is it important to determine the material mechanical properties Table (1). Material characteristics are those which affect the mechanical properties and ability of a material to be folded in suitable shape under the crash force to increase the energy absorption conventionally.

Properties of Structure Steel under Standard Conditions (t= 20°C)				
Density (kg/m^3)	*Elastic Modulus (N/m^2)*	*Shear Modulus (N/m^2)*	*Yield Stress (N/m^2)*	*Poisson's Ratio*
7800	210 (10^9)	77 (10^9)	240 (10^6)	0.31

Table (1): Carbon Steel Welded Tubes (ST37) Properties [11].

Theory of crash behavior through a progressive folding pattern during apply impact load on axial members discus the relations between applied load with deformation. Also discuss a suitable design to produce enough stiffness and energy absorption to prevent the occupant's compartment. The expression for the mean crush load is derived from the energy balance by equating the external work done by the crush load with energies dissipated in deformation [7].From the equation (3)can be found the applied moment in fully plastic duration by define the sample material properties and the wall thickness

$$P_{mean} = 38.27\, M_o\, C^{\frac{1}{3}} t^{\frac{-1}{3}} \quad (1)$$

$$P_{max.} = 9430\, b^{0.14} t^{1.86} \rho_F^{-0.43} \sigma_y^{0.57} \quad (2)$$

And from previous equations plus some specifications of the samples can be analytically produce maximum applicable load and average load

$$M_o = \frac{\sigma_o t^2}{4} \quad (3)$$

$$\sigma_0 = (0.9 \sim 0.95)\, \sigma_u \quad (4)$$

$$C = \frac{1}{2}(b + d) \quad (5)$$

The equations (1) and (2) are define an empirical equation to calculate average and maximum loads on the square section to estimate the reference sample capacity before the tests [8].Where M_o is the fully plastic moment, $\sigma_o$is the average flow stress, σ_u and is the ultimate tensile strength of the material, ρ_F material strain hardening factor, σ_y is the material yield strength, b and d are the width and height of the column, for a square tube, for which C = d = b, t is the wall thickness [9].

Description of Test Samples

The material properties, geometry shape and material thickness of a front column have major influence on the structural crashworthiness behavior and its energy absorption capability. This section will focus on comparing two of design guidance in the crash energy management aspects related to structure manufactured from steel tubes and find the effect of geometric profile. Details of the samples dimensions and cross-sections are given in Table (2). The test samples are 300 mm length, which were statically crushed in universal testing machine. The samples were fabricated from 1 mm and 1.8 mm thin cold rolled steel, having an ultimate strength of 370MPa. The formed samples can be divided into two groups, the first according to the cross-section dimensions and the second according to the sample wall thickness.

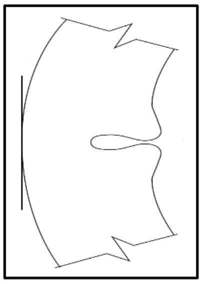
Table (2): Mass, geometry and dimensions of the tested samples.

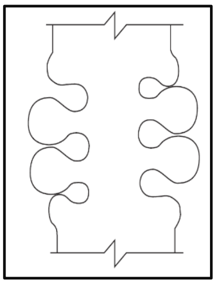
Samples Dimensions mm	Sample 1	Sample 2	Sample 3	Sample 4
	Square 30x30x1 L=300	Square 30x30x1.8 L=300	Square 20x20x1 L=300	Square 20x20x1.8 L=300
Samples Mass (kg)	0.35	0.73	0.24	0.425

Deformation Analysis of Thin Walled Tubes

In this study, mainly focused on the deformation behavior of two different width of thin-walled steel tubes, when subjected to a large axial impact force. The collapse behavior of the tested sample is related to its thickness/width (t/b) ratio and material properties. The typical dimension of the thin-walled member is, its height= 300 mm, two samples with width= 20 and 30 mm, and the first thickness is = 1.8 mm. The proposed two samples with width= 20 and 30 mm, but the thickness is = 1 mm, the material properties of the members are given by Young's modulus E = 210x103 MPa and Poisson's ratio ν = 0.3. The deformation behavior of a structure member will be influenced by its section dimensions.

- For very small t/b ratios at $\frac{1}{60} \geq \frac{t}{b} \geq \frac{1}{120}$ representing the so called "non-compact" sections in which the local buckling strength is considerably below the material yield strength
- For larger t/b ratios at ($\frac{t}{b} < \frac{1}{60}$) typifying the "compact" sections in which the elastic buckling strength exceeds material yield strength.The collapse mode will appear very stable even in the presence of considerable geometry or loading imperfections [1].





a) Buckling deformation mode b) Collapse deformation mode

Figure (2): Deformation behavior of thin-walled square steel tubes.

III. Experimental Evaluation of Axial Steel Tubes of Bus Front End Structure

Description of Testing Machine

This section deals discussing the method and steps of the tests on the samples that provide a major portion of the energy absorption and evaluate the stiffness undergo large plastic deformations of square steel tubes.Computer-controlled universal testing machine (JINAN, Model No: WDW-300) and the maximum load of 300 KN, it is suitable for compression test for metal, rubber and plastic. The test speed between 0.1-250 mm/min, length of compression space is 700mm, Compression tests were carried out in 300 kN, four longitudinal specimens as shown in Figure (4). The specimen was compressed 100 mm at a rate of 50 mm/minute.The aim of these tests is to measure the deformation versus applied force [11].

Figure (4): Universal testing machine

Experimentally Damping Coefficient

The loss factor is the most commonmeasuring factors. The estimated damping coefficient in Half-power bandwidth method is based on the force-deformation response. Damping evaluation is a general method based on the force dissipation behavior, results of sample testing can be used to evaluate the damping in single member or complete structure. Loss factor can be successfully applied in case of nonlinear systems. loss factor is the ratio of bandwidth Δδ is defined as the width of the deformation response curve when the magnitude is $\frac{12}{\sqrt{}}$times the peak force

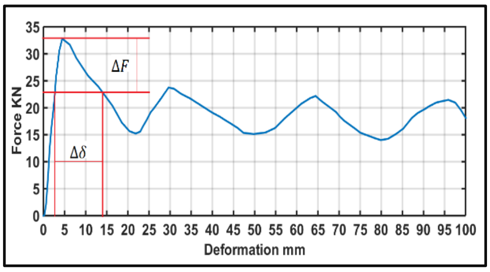


Figure (5): force-deformation response

Many experimental methods such as the (Half-power bandwidth method) used for samples material and structures evaluate modal damping in the form of a characteristic curve. Derivation of a force-deformation response is required Figure (5), damping ratio can be determined using the expression.

$$\text{Loss factor} = \frac{\Delta\delta}{\delta at\ fmax} \quad (6)$$

$$\text{Damping ratio } \xi = (\frac{1}{2}(\frac{\Delta\delta}{\delta_{fmax}})\ ) \quad (7)$$

$$\text{Damping Coefficient } C = \xi . Cr = \xi . 2\sqrt{k_{eq} . m} \quad (8)$$

RSM Optimization Technique

This section addresses the energy absorption performance and the parameters of cabin structure optimization which is composed of nested thin-walled square tubes. The optimization tends to display modified characteristics to withstand the crash force with smoother deceleration level in a minimum intrusion. The authors develop a sample of the square thick-walled structure, in which the objective function is to maximize the strain energy absorption of the bus front cabin structure, the design variables are the dimensions of one sample of the structure members.

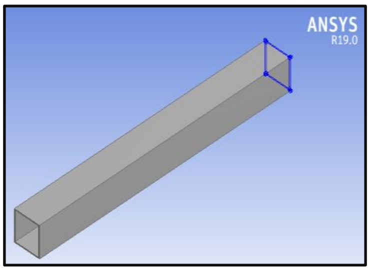


Figure (6): Square steel tube geometry shape of bus structure sample

The square section sample of the bus front cabin as in Figure (6) was analyzed to optimize its strain energy as potential energy according to the variation in thickness and width. The responses of acceleration, velocity and displacement results of bus crash tests. The deceleration curve has high response caused by the erratic crumpling of the typical bus structure specifications. The front crash zone members are expected to absorb the collision energy based on the structure member behavior, the current work discuss the influence of the width and the thickness of the structure member of bus cabin, the objective function is to optimize the sample dimensions to maximize the energy absorption as much as possible. And neglecting the influence of vertical force during the optimization process. The objective of the RSM optimization is lead to the eventual folding collapse of the section. The Response Surface Methodology (RSM) problems are solved by using the element dimensions as design variables. The trade-off between the thick wall and the thin wall of cabin structure sections to estimate the required behaviour based on the stiffness and damping to reduce the deceleration level during the frontal collision with neglect the influence of vertical loads. The optimization target is to maximize the absorbed energy based on the change in the structural characteristics of the bus cabin.

IV. Bus SectionDesign Characteristics

Bus Section Collapse Mechanisms

During the event of bus rollover, most of the plastic deformation of bus structures are in bending mode of the members. The bus structure failure behavior depending on the weakest point in the structural. So, collapse behavior depends on the structure design considerations and the assembly process. hence, whenever any four points are formed as hinges, bus section collapse will take place. there are three main types of the collapse behaviors. The possible collapse mechanism behavior can be clarified in the three shapes in Figure (12) and the integrity of other members to get the desired collapse method.

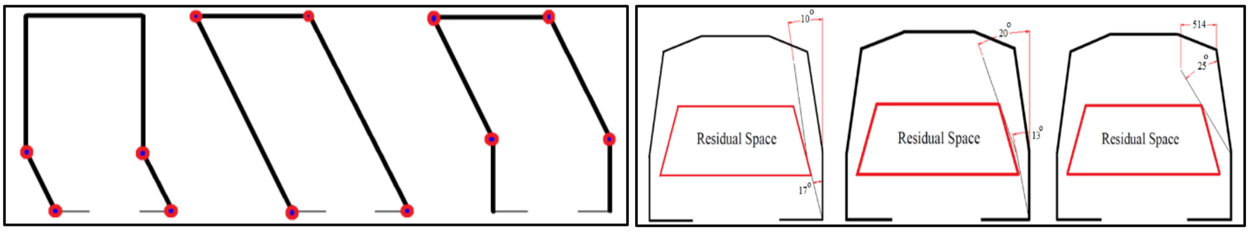


Figure (12): Bus Section Collapse Mechanisms

Bus Section Rollover Using ANSYS Static Structure and Experimental Evaluation

Simplify the bus geometry from the full model to section model and Importing the geometryinto Ansys Software, the bus section consisted ofsquare steel tubes with different dimensions and thickness.

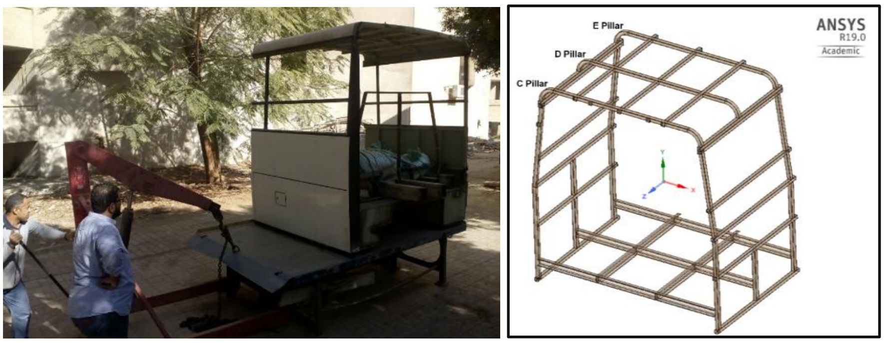


Figure (13): Bus Section Geometryand actual section on Tilt-table During Rollover Test.

Experimental Rollover Test Procedures

After preparing the section of the bus structure to implement the rollover test and analyze the behavior and obtained by attaching the gross weight up to 1650 kg on occupants' seats and bus ground surface. The bus section is installed on the tilting platform, which is rotated around the axis of the tilting using Hydraulic lifting crane.

1. The test was performed on a flat concrete surface
2. Tilting platform height is 800 mm and the distance between the structural support element and the center of tilt-table rotation no higher than a 100 mm.
3. Preparing the area of the residual spaceand markto measure the inclination after the test
4. Add the required weight to the bus body-section to gross section weight.
5. The platform raises in low speed 5 deg/sec up to the limit position of instability.
6. Separation time of the bus section from the stability until contacts with the ground.

Figure (14): Tilt-table height level and side support

V. Results and Discussion

Occupant protection during the collision includes two opposing factors, the structure intrusion and the deceleration level. In case of a lower deceleration, the structure needs to more gradual flexibility, sometimes the result is more intrusion and deformation but safer deceleration level. It is necessary to search for the factors that can be used to increase the collision energy dissipation. The energy dissipation components in the bus front end structure are the square steel tubes. RSM optimization method to maximise the energy absorption with minimum deformation of square steel tubes characteristics such as section width and wall thickness.

Experimental Results of Commonly Used Design

The energy dissipation in a frontal crash normally occurs by deformation of the longitudinal members. The actual samples of bus structure members with 1.8 mm wall thickness giving buckling behavior. Tests have been executed to evaluate the influence of two of the design parameters on the crash behavior, where the goal for these tests is to determine the different between the actual and required (optimized) characteristics. The Implementing of a quasi-static compression test approach. They start with a premise that thick-walled box columns subjected to axial compression, it will buckle locally when critical stress is reached. The deformation of the square section is related to its thickness/width (t/b) ratio and material properties.The samples with (1.8mm) thickness, absorbing the impact energy in between 1.2 to 1.6 kJ in the intrusion of 100 mm from the member length and the decreasing in absorbed energy because of the bending behavior, the absorbed energies of all tested samples have a proportional relation to the deformation characteristics.

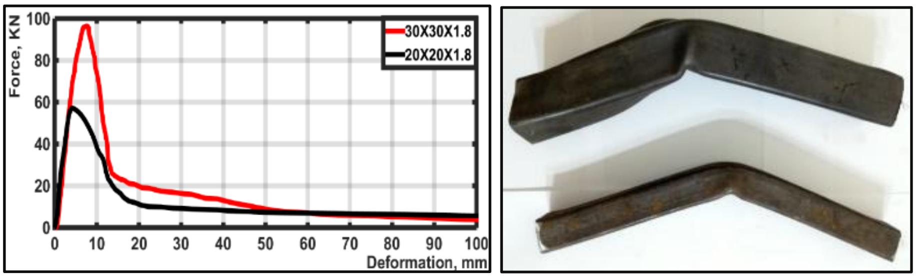


Figure (7):Force-deformation behavior of steel tubes with 1.8mm thickness due to compression test

The sample with the dimensions of (30 x 30 x 1.8) registered the highest value of peak force as shown in Figure (7) but the bending behavior lead to minimize the energy absorption, which reached 1.62 kJ in 100 mm of the sample length. The sample with the dimensions of (20x20x1.8) registered the lowest value of energy absorption, which reached 1.2 kJ in 100 mm of the sample length

Optimized Design Parameters of Axial Members

RSM optimization strategy presents a method for compares the influence of the sample thickness in between 1 mm into 3 mm and width of structure member in between 20 mm to 40 mm versus the energy absorbed. Energy absorption behavior is the most important indication parameters in the structure safety during frontal collision.

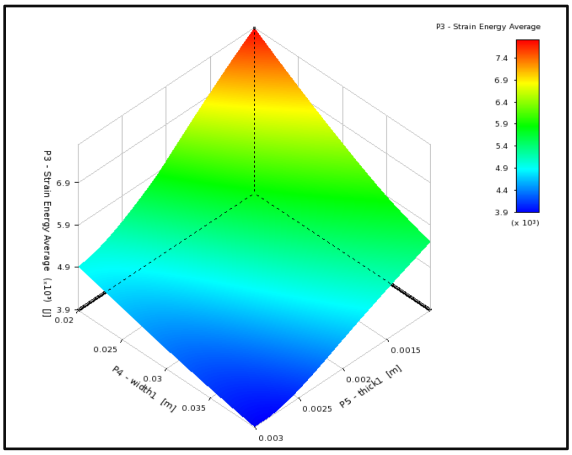


Figure (8): Strain energy verses the square tube thickness and width

Energy absorption performance of the frontal structure depended up on the structure layout and dimensions, optimization was conducted in this paper based on two principal design parameters. Strain energy is stored within a structure elasticity when the structure members is deformed due to loads, strain energy is a one type of potential energy. Other energy losses, such as damping or yielding, friction. The strain energy is equal to the energy absorption on the structure components by accumulated force to the change in the displacement.

Experimental Validation of Optimized Design Parameters

The samples with a wall thickness (1mm) registered higher values of energy absorption which reached between 1.8 to 2 kJ due to the ideal collapse behavior of the thin wall samples undertheseconditions. The absorption energy of the sample (30x30x1) registered higher value Figure (9), even though the peak force not high but the continuity of the mean crush force in their natural rates according to the collapse characteristics which in turn led to a rising the energy absorption. In the same way, applied to the other sample (20x20x1) with different values.

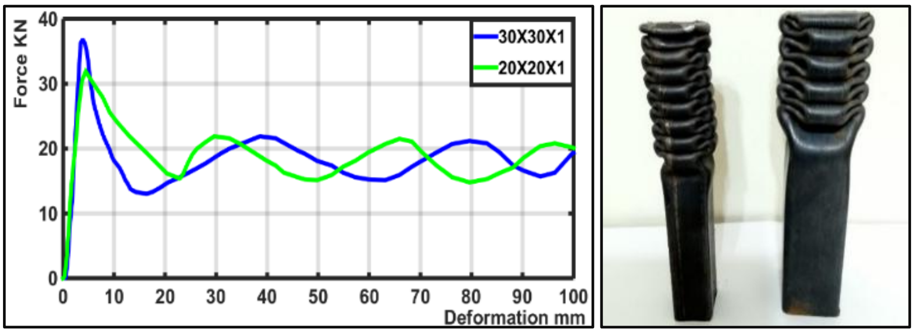


Figure (9):Force-deformation behavior of steel tubes with 1mm thickness due to compression test

The value of specific energy absorption of the section (20X20X1) Considered the highest energy absorption as 7.5 kJ/kg as shown in Figure (10). The benefit of every 1 kg of the frontal structure weight to withstand 7.5 kJ of the collision energy.

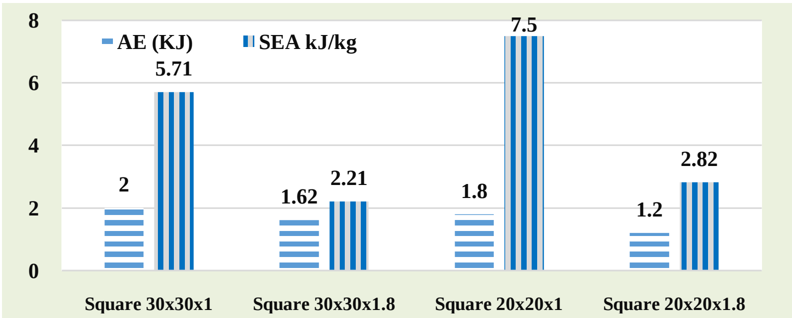


Figure (10): Absorbed Energy (AE) and Specific Energy Absorption (SEA) according to thetested samples.

Four different cases are used, two different dimensions of cross-sections cases and two-variable thickness are used to compare the influence of the member design parameters on the collision performance as a primary study.

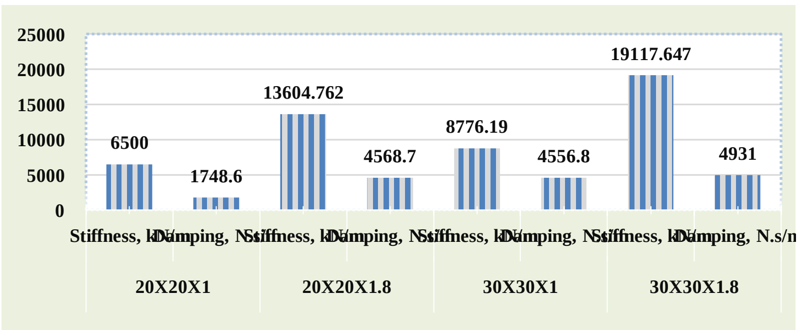


Figure (11): Stiffness and damping of four differentthe testedsamples.

Rollover Results ofBus Section Typical Design

The simulations are performed with ANSYS 19. Unfortunately, the test has been failed due to some defects in the welding of side rails and the roof members, that need to repeat the test in the future after the modifications.As shown in Figure (15). the bus superstructure fails at the shown welding points, and to avoid the failure points of bus structure, we can increase the cross-section of the structure steel tubes with minimize the section thickness to increase the structure dissipation, but that will increase the overall weight of the bus. hence, it is advised to add stiffeners members or supportive sleeve, it adds less weight and increases the strength of the bus against rollover.Experimentally, Tilt-table was provided horizontally on flat ground level at a vertical height of 0.8 m. Maximum tilting rate of 5 degree/sec, axis of rotation of the Tilt-table is located 100 mm below the platform and 100 mm from the vertical wall of the ditch. A side support stopper was provided to support for the roll center so that the bus section would tip-over from the platform without side skid. The stopper dimensions are 500 mm and 20 mm in length and width respectively.After preparing the section of the bus structure to implement the rollover test and analyze the behavior and obtained by attaching the gross weight up to 1.65 ton on occupants'seats and bus ground surface. The bus section is installed on the tilting platform, which is rotated around the tiltingaxis.

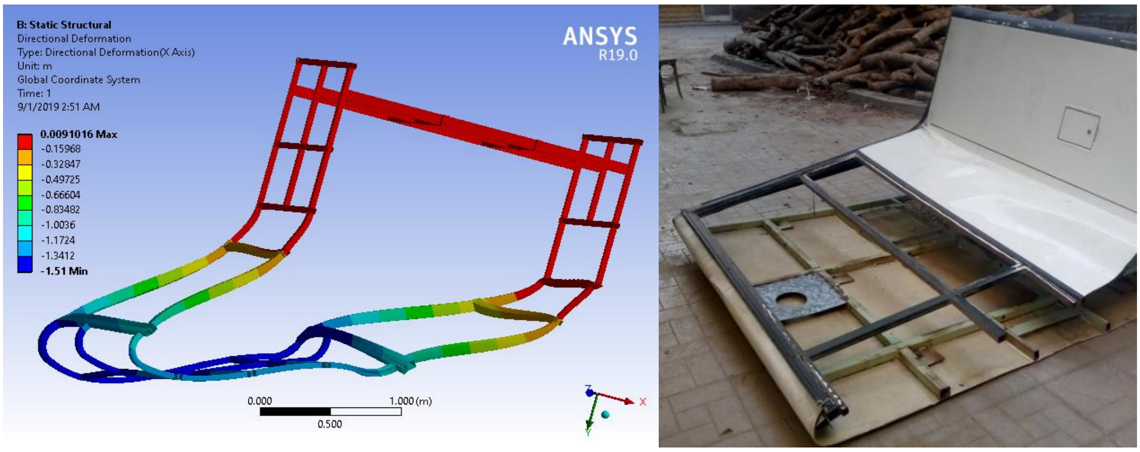


Figure (15): Experimental and numerical simulation of the bodysection.

Topology Optimization and Weight Reduction

Topology designs for structural shape and size. The recommended optimization process which is concerned with the structural engineering issue of distributing a constrained amount of material in a design space. based on the use of mathematical programming and finite elements. The structural pillars absorb the impact energy during the overturning collision. So, it's necessary to optimize the structural members and remove unnecessary weights. Topology optimization method consider as one of real tools for least weight and perform the objective design based upon the operation states. The current case of the bus section, the load is applied laterally in the upper corner of the bus section. The structure is symmetric along the roll axis, but the longitudinal friction force gives different structure deformation and almost need for redistribute the structure shape. The bi-directional evolutionary optimization (BESO) technique is used to search for the economy and safe design in the complete domain by progressively adding and removing material. Filtration techniques are used to select the best geometry in the design environment and to eliminate unnecessary structural materials and details. Validate the optimized structure according to topology optimization method is presented to demonstrate the capability and effectiveness of the proposed method.

Mass constraints: 40%
Number of design variables: 294914 cells
Design variables: Density of each design cell
Subjected to: Lateral and longitudinal forces in (X and Z) directions

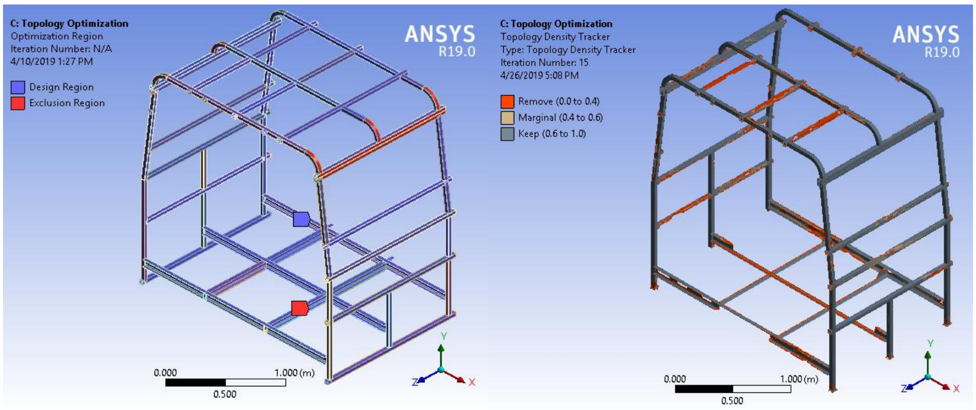


Figure (6.35): Optimization region and exclusion region of bus section and organic shape and material density.

V. Conclusion

The following items can be concluded from both simulation and experimental results:

- Behavior of the typical structure member with thickness 1.8 mm tended to be buckling.
- Optimization results using RSM indicated that energy absorption is increased when reducing the thick. to 1 mm.
- Optimization results of proposed structure member dimensions is validated experimentally.
- Both simulation and experimental results agree with each other, in other words the test has been unfortunately failed due to some defects in the welding of side rails and the roof members; because the structure main pillars assembled as welded pieces.
- Optimization results indicate that the structure endure these forces in the three directions and can even be minimize the weight or at least redistribute the structure geometrical shape.

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