Simulating Metamodel for Urban Bus Seats Design

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Abstract. The finite element analysis is useful to predict the displacements and strength of the components of an urban seat bus. However, this analysis has a high computational cost when explicit dynamic technique is applied. This work uses Ansys LS Dyna software to carried out a complete 3D static test of an urban seat bus according with the Regulation No. 80 of the Economic Commission of the United Nations for Europe. To reduce the computational cost, we applied a bidimensional frame analysis (metamodel) using direct matrix method to obtain nodal displacements in 12 different models. The variables of this study were: thickness, sections and length of structural elements in order to optimize the strength of the seat. The results showed a range of variation about 0.1 % to 3.0% between finite elements analysis and metamodels. Finally, it was proved that metamodels reduce the time analysis and can be used in a pre-design stage.

1. Introduction

In the automotive industry, structural seat design is one of the most important aspect because it is necessary to ensure the users safety requirements. By other hand, the correct structural seat design could decrease the fuel consumption and environmental pollution due to reduction of the seat weight, especially in the large vehicles like the bus passengers [1, 2]. When the bus suffers a frontal crush, it can produce a “domino effect” on the seats, causing injuries in the passengers. It is due to a failure in the anchorage strength and breakage of the seat structure [3-5]. Bus seats must be able to resist the hit of head and knee of the back passenger; at the same time the structure will not be too rigid to absorb the energy during an accident, as well as the seat anchors must not be pulled off from the bus floor [6]. The optimization of the seat structure weight can be obtained substituting the conventional materials and applying modern design techniques. [1, 7, 8].

In order to guarantee the safety of the passenger seat, Regulation No. 80 of the United Nations Economic Commission for Europe establishes requirements for approval large vehicles seats, for passengers transportation concerning the resistance of the seats and their anchors. Its regulation stipulates: a) the seats must be installed facing forward in vehicles of categories M2 and M3, classes II, III and B; b) vehicles of categories M2 and M3, classes II, III and B, concerning to the anchorages of passenger seats and the seats installation [9].

The time used to structural design and optimization of the seat can be reduced applying metamodels, they have been used for particular applications, like in Abasolo’s investigation [10] where, by a discretization of the component and using two freedom degrees elements and equivalent stiffness, obtained from the three-dimensional simulation of the component by finite element software, a metamodel was elaborated to simulate the sequences of screwed joints of wind turbines and the results obtained were
very similar comparing to the finite element method. Other research used a metamodel [11], to simulate dummy vibration modes in a car seat, obtaining a reduction of computational analysis time from 36000s to 36s with acceptable margin of error to compare with original model simulation.

The objective of this work is to develop a parameterized metamodel to estimate the structure displacements of the urban bus seat according to the static test described in the ECE R80 regulation, based on the results obtained by simulations using finite element analysis in the software Ansys Ls-Dyna.

2. Methodology
The model used is an individual urban plastic seat. It has two structural steel pillar to support the seat and the structure is attached to the bus floor by 10mm bolts (figure 1a, 1b)

![Figure 1. Parts of the seat structure (1. Back support 2. Base support 3. Connection of the pillar base 4. Pillar 5. Connection between pillar and bus structure 6. Bus structure 7. Low impactor 8. Top impactor).](image)

The 3D CAD geometry of the seat structure was modeled in Ansys SpaceClaim software. The conditions for the experiment are described in Appendix 5 about the requirements and procedure related to the static test in the ECE-R80 regulation [9]. An explicit dynamic analysis of the seat structure was carried out using shell elements. The maximum size of elements was 5mm, the shear correction factor was 0.83333, the number of integration points 3, the thickness of elements is considered uniform. The thickness of back support, base support, connection of base to pillar, pillar, connection between pillar and bus structure were 2 mm and materials according to table 1.

The bus structure (part 6, figure 1b) are restricted in all degrees of freedom. The seat elements and impactors had automatic contact (* CONTACT AUTOMATIC SINGLE SURFACEID); In addition, penetration between parts was restricted. The impactors were assigned as totally rigid bodies [14].

The properties of materials used in the seat components were defined by modeling materials MAT ELASTIC and MAT PIECEWISE LINEAR PLASTICITY, the last one allows define the behavior of the elastic and plastic zone [15]. These properties are shown in Table 1. The applied load in the upper impactor was $F_1 = 1400N$ and in the lower impactor $F_2 = 4000N$ those in the horizontal direction and constant during 0.2 seconds.
Table 1. Features of material models used in Ansys-LsDyna.

| Properties of MAT_ELASTIC for seat belt |
|-----------------------------------------|
| Density [kg/m³] | Young modulus [MPa] | Poisson coefficient |
| 1390 | 110000 | 0.3 |

| Properties of MAT_ELASTIC for the joints |
|-----------------------------------------|
| Density [kg/m³] | Young modulus [MPa] | Poisson coefficient |
| 7890 | 200000 | 0.3 |

| Properties of MAT_PIECEWISE_LINEAR_PLASTICITY for ASTM A500 steel |
|---------------------------------------------------------------|
| Density [kg/m³] | Young modulus [MPa] | Poisson coefficient | Plastic deformation of break | Yield strength [MPa] | Plastic deformation of failure | C | Deformation velocity | P | Deformation velocity |
| 7890.00 | 200000.00 | 0.30 | 0.283 | 320.00 | 0.370 | 40.00 | 5.00 |

| Properties of MAT_PIECEWISE_LINEAR_PLASTICITY for ASTM A500 no liner behavior |
|--------------------------------------------------------------------------------|
| Density [kg/m³] | Young modulus [MPa] | Poisson coefficient | Plastic deformation of break | Yield strength [MPa] | Plastic deformation of failure | C | Deformation velocity | P | Deformation velocity |
| 0.0000 | 0.01092 | 0.03959 | 0.04388 | 0.04817 | 0.1431 | 0.2545 | 0.4000 |
| 320.0 | 320.00 | 347.16 | 351.22 | 355.28 | 382.07 | 341.91 | 0.00 |

The simulation results of the complete seat let to generate a metamodel with the quality of reproducing the displacements of the structure elements after applying the loads for static test, considering the structural element where the Force 1 of the impactor take place will be displaced horizontally, also to rotating it around the z-axis, and where Force 2 of the lower impactor is located, there will be a horizontal displacement and a rotation around z too. Consequently, the metamodel that is needed for the proposed case must have elements with three freedom degrees in the plane, we concluded, the displacements that influence in greatest way on the overall seat behavior of the during the test are: along the axis X, Y axis as well as around the Z axis.

The frame type element was used for the schematization of the metamodel, it counts with three freedom degrees, equivalent section and equivalent stiffness correspond to the seat structure parts determined from the Ls-Dyna simulation. The elements were divided according to the points which is necessary to apply loads or know their displacement, taking as a reference the complete seat simulation result. One node was placed in each point to determine the vertical displacements Y, horizontal X and rotational around the Z axis, obtaining a model that is shown in figure 3.

From the obtained metamodel, parts thicknesses, profiles sections, pillar angle, elements length, magnitude and application of loads were parameterized, facilitating the structure optimization and verifying its resistance. The identified variations in the parametrized metamodel were verified by three-dimensional Ls-Dyna simulation.

3. Simulated metamodel

3.1. Metamodel obtaining

By seat structure simulating in Ls-Dyna were identified the displacements in the points where the loads were applied with values around 113 mm in the upper impactor and 83 mm in the lower impactor as shown in figure 3a). From the three-dimensional model, nodes 3667, 2964 and 389 were labeled, which provide us the maximum displacements required for verifying compliance with the ECE R80 regulation. The other nodes were determined based on variation of section and stiffness of the parts, this supported to determine the more approximated metamodel to the three-dimensional
The metamodel of 12 nodes and 11 elements shown in figure 3. The element L1 with its nodes 1 and 2 represents a bolt, node 1 is placed as fixed support restricting in all degrees of freedom, while node 2 will have the six degrees of freedom simulating the interaction between the pillar connection with the bus structure and bolt. Element 2 and its nodes 3 and 4 represent the other bolt, node 3 is considered similar to node 1 and node 4 as node 2, representing the interaction between the connection on the other side.

The element L3 and L4 with the nodes 2, 4 and 5 represents the connection between pillar and structure of the bus where the pillar component joins. The pillar is represented in two sections by elements L5 and L6 with nodes 5, 6 and 7; the last one represents the connection of the base with pillar, the element L7 with its respective nodes 7 and 8 represents the base support, the elements L7, L8, L9, L10, and L11 with the nodes 7, 8, 9, 10, 11 and 12 represents the back support. This discretization was made considering the points of equivalent section change, equivalent stiffness change, contact of the impactor with the back support, the maximum seat height and results of three-dimensional finite elements analysis.

3.2 Metamodel acceptance
The equation that solves the metamodel, considering the discretization of figure 3, is necessary to determine the displacement on the X axis of node \( i \), \( \delta_{xi} \); displacement on the Y axis of node \( i \), \( \delta_{yi} \); \( \theta_{zi} \) rotational displacement around the z axis of node \( i \), obtaining a 12x3 freedom degrees system.
The forces produced by the upper and lower impactor on the back support are called $F_{x11}, F_{x22}$ respectively. The constitutive matrix equation of each element corresponds to (1) and (2):

$$\begin{bmatrix} A_i c_i^2 + \frac{\mu_i}{\xi_i} S_i^2 & (A_i - \frac{\mu_i}{\xi_i}) c_i S_i & -\frac{\mu_i}{\xi_i} S_i & -\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} S_i \\
(A_i - \frac{\mu_i}{\xi_i}) c_i S_i & A_i S_i^2 + \frac{\mu_i}{\xi_i} c_i^2 & \frac{\mu_i}{\xi_i} c_i & -\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} S_i & -\frac{\mu_i}{\xi_i} S_i \\
-\frac{\mu_i}{\xi_i} S_i & \frac{\mu_i}{\xi_i} c_i & A_i \frac{\mu_i}{\xi_i} c_i^2 & \frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} S_i & -\frac{\mu_i}{\xi_i} S_i \\
\frac{\mu_i}{\xi_i} c_i & \frac{\mu_i}{\xi_i} c_i & -\frac{\mu_i}{\xi_i} c_i S_i & A_i \frac{\mu_i}{\xi_i} c_i^2 & -\frac{\mu_i}{\xi_i} S_i & -\frac{\mu_i}{\xi_i} S_i \\
\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} c_i S_i & 4L_i & A_i \frac{\mu_i}{\xi_i} c_i^2 & -\frac{\mu_i}{\xi_i} S_i \\
\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} c_i S_i & -\frac{\mu_i}{\xi_i} c_i S_i & 4L_i & A_i \frac{\mu_i}{\xi_i} c_i^2 & -\frac{\mu_i}{\xi_i} S_i \\
\end{bmatrix} \times \begin{bmatrix} \delta \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \delta \end{bmatrix} = \begin{bmatrix} \delta \end{bmatrix} \tag{2}$$

Where:

- $c_i$ = Cosine of the angle at which the element is oriented
- $K_i$ = Element equivalent stiffness
- $A_i$ = Area or equivalent section of the element
- $L_i$ = Element length
- $I_i$ = Inertia of the element
- $E_i$ = Elastic module of each element
- $S_i$ = Seno of the angle to which the element is oriented
- $c_i$ = Cosine of the angle at which the element is oriented

The assembled global equation of the metamodel includes the elements from 1 to 11 corresponds to a $36 \times 36$ matrix. From the solution of the mathematical model, considering the boundary conditions of each node, obtaining the displacements in the X, Y, and rotation around the Z axis that compared to the results of the Ls-Dyna simulation a maximum error of 2.98% was recorded, indicated in table 2.

### Table 2. Obtained displacements in Ls-Dyna comparing with metamodel.

| Node | Metamodel | Ls-Dyna Simulation | % error |
|------|-----------|--------------------|---------|
|      | Ls-Dyna  | Horizontal | Vertical | Horizontal | Vertical | Horizontal | Vertical |
| 1    | 8856     | -0.26      | 3.01     | 0.00       | 0.00     | 1.00       | 1.00     |
| 2    | 11324    | 0.41       | 11.17    | -0.13      | 0.02     | 1.30       | 1.00     |
| 3    | 8879     | 0.02       | -3.41    | 0.00       | 0.00     | 1.00       | 1.00     |
| 4    | 8758     | -0.11      | -3.96    | 0.21       | -0.02    | 2.89       | 0.99     |
| 5    | 11266    | -0.07      | 3.23     | 0.06       | -0.11    | 1.95       | 1.03     |
| 6    | 11899    | 20.92      | -9.34    | 23.90      | -13.87   | 0.14       | 0.48     |
| 7    | 297      | 43.82      | 0.60     | 48.52      | 0.34     | 0.11       | 0.43     |
| 8    | 352      | 44.52      | 13.24    | 48.52      | 17.77    | 0.09       | 0.34     |
| 9    | 389      | 61.13      | 25.77    | 67.97      | 37.20    | 0.11       | 0.44     |
| 10   | 228      | 88.07      | 24.28    | 85.06      | 38.69    | 0.03       | 0.59     |
| 11   | 2964     | 103.30     | 22.29    | 112.42     | 41.09    | 0.09       | 0.84     |
| 12   | 3667     | 167.10     | 29.50    | 159.21     | 45.18    | 0.05       | 0.53     |

The experiment was repeated modifying the thickness of the back support, base support and pillar with values of 1, 2, 3mm, obtaining a maximum variation of 2% between the metamodel and LS-Dyna results.
shown in table 3. The greatest variation occurs at lower thicknesses and this could be due to effect of plastic deformation in the elements.

Table 3. Results variation of displacements analyzed by metamodel and FEM.

| Part        | Thickness (mm) | Variation |
|-------------|----------------|-----------|
| Pillar      |                |           |
| 1           | 2%             |           |
| 2           | 1%             |           |
| 3           | 1%             |           |
| Base support|                |           |
| 1           | 1%             |           |
| 2           | 1%             |           |
| 3           | 2%             |           |
| Back support|                |           |
| 1           | 2%             |           |
| 2           | 1%             |           |
| 3           | 1%             |           |

4. Conclusion
A metamodel and parametric model has been created for an urban bus seat, it allows knowing the displacements of the seat structure after applying the loads established in the ECE R80 regulation and verifying the compliance with its resistance, with variations less than 2% compared with results of the finite element analysis. In addition, a new methodology has been developed, by using of metamodel and parameters variation, allows be able to optimize thicknesses, sections, lengths of the elements, improving the model structure design and reducing computational costs and time in the design stage.

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