

Numerical Simulation in the Design Process of Foam Seats for the Automotive Industry

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Abstract: In the development of foam seats, there are many design variables and design requirements to be taken into account. In this context, numerical simulation can be a valuable tool to facilitate this process and shorten its duration by minimizing the number of test specimens built and the number of real tests made. In general, the aim is to predict the response of a seat under certain conditions and optimize its design with respect to static and dynamic comfort, both from the geometric and material points of view.

The work presented in this paper is the result of a preliminary feasibility study carried out within the context of a more ambitious program. This program is aimed to virtually evaluate seat cushion comfort by integrating geometric design, material databases and mechanical simulations under the same working environment.

This study is focused on the assessment of the application of numerical simulations done with ABAQUS in the development of car seat cushions made of polyurethane foam. First, mechanical simulations of simple tests were carried out using a hyperelastic constitutive model of ABAQUS in order to adjust its parameters with real test data. Then, a static indentation test, which reproduces the mechanical response of a seat under the load of a dummy occupant, was simulated. The indentation curve was validated with real test results in a first approach. Validation of the contact pressure field is still to be done.

Keywords: Car seat, polyurethane foam, hyperfoam, indentation.

1. Introduction

Seat cushions, backrests, headrests, armrests, and other foam parts that form the seat function in vehicles, are developed taking into account four principal design criteria: integration in the vehicle, safety, comfort and aesthetics. These four criteria involve many requirements which have to be simultaneously satisfied in the design process, where design is optimized with respect to certain variables.

In the design process of car seats there are many design variables to be considered. These design variables are mainly related to geometry of the seat part considered and to its material. The difficulty lies in the fact that mechanical properties of foam materials highly depend on their strain level. This implies that usually several test specimens must be built to test their response and verify the satisfaction of the design requirements. To get an specimen ready for testing may take several weeks: first, the mould with the desired geometry must be built, then, the specimen is created in this mould and, finally, certain time is necessary for the specimen to be ready to be tested.

The high number of design requirements to be satisfied, the high number of design variables, and the complexity inherent to the foam material make the design process of foam seats and their optimization complex and time consuming.

In this context, numerical simulation may be a valuable tool to facilitate the design process and shorten its time by minimizing the number of test specimens built and the number of experimental tests made. This is the motivation of developing a virtual environment, which integrates numerical simulation in the decision-taking process of the design process of foam seats. In general terms, the aim is to predict the response of a design under certain circumstances and, from this information, to optimize its geometry and material according to certain design requirements. In the present work, attention is focused on requirements related to comfort criteria.

The work presented in this paper is a preliminary feasibility study, which was done in the frame of a more ambitious program, currently underway, aimed to develop this environment. This study is focused on the assessment of numerical simulations done with ABAQUS (ABAQUS, 2006a) in the development of car seat cushions. Moreover, results obtained from those simulations are related with comfort.

In Section 2, general remarks about comfort assessment and its relation with results obtained from static and dynamic tests are given. A brief description of the main characteristics of the global environment planned to integrate the different aspects of design process of vehicle foam seats is given.

In Section 3, the general methodology of numerical simulation of the static indentation test on foam seats is described. Two steps are clearly differentiated: fitting of the general constitutive material model for elastomeric foams to the particular case considered and simulation of the static indentation test itself. Both are explained and results obtained for the static indentation test on a seat cushion are given.

Finally, conclusions are drawn in Section 4.

2. Virtual environment of comfort assessment

Ergonomics and comfort are key factors to determine suitability of a car seat. In a broad sense, seat comfort involves such different aspects as texture, stiffness or smell. In the present paper, only mechanical factors are considered.

In this section, a global vision of a virtual environment which integrates numerical simulations of mechanical tests in automotive seats and one of its most relevant design criterion, i.e. comfort, is given.

Seat comfort in vehicles is studied both under static and dynamic conditions. One of the difficulties inherent to comfort assessment is to translate comfort sensation into quantifiable variables in order to *measure* comfort from the mechanical point of view.

There are several studies (Guerin, 2003) (Mills, 2000) (Verver, 2004) that analyze the influence of different variables on comfort and validate different occupant models and seat models for numerical simulations of comfort tests. Under static conditions, comfort is assessed with variables related to occupant's position on the seat, to its position with respect to the vehicle, and to the pressure distribution on the contact surface between occupant and seat. In dynamics, in addition to these variables, other variables related to transmission of vibrations from the seat to the occupant are considered.

Typical variables related to occupant's position are the angle between seat cushion and backrest, the angle between seat pad surface and horizontal plane, and the angle at certain occupant's joints (Bubb, 2000) (Judic, 1993) (Polyurethane Foam Association, 1992).

Hip-point, also called H-point or Seat Reference Point (SRP) is the joint point between occupant's femur and pelvis. This point is widely used in industry to identify the height at which driver has an adequate visibility according to certain criteria. This point location is crucial for safety, ergonomics and comfort.

Pressure distribution is one of the most important variables in both static and dynamic comfort assessment. Under ideal conditions, the geometry of the seat and its material should be able to provide a uniform distribution of the occupant's weight, avoiding areas with pressure peaks. Areas with high contact pressure indicate eventual blood flow restrictions causing discomfort and, in extreme cases, pressure ulcers. In laboratory, pressure distribution can be obtained by using sensor blankets in the indentation tests. But this pressure field can be also obtained from numerical simulation of these tests.

Many studies have established a relation between comfort and contact pressure distribution between occupant and seat (Verver, 2004). In this context, some of the relevant parameters of the contact pressure distribution are mean pressure, maximum pressure, symmetry of the distribution, thigh pressure, lumbar pressure, contact area and shear stresses. In general terms, those factors yielding a more uniform contact pressure distribution will improve comfort.

In the design process of automotive seats, comfort is often assessed in comparison with previous seat designs. However, there are studies which suggest absolute values of certain variables, which can be used as absolute reference to evaluate comfort of a certain design. For guidance, a seat is considered to have an acceptable comfort level if contact pressures between occupant and seat are in the range between 8000 Pa and 16000 Pa (Seigler, 2002). These range limits match with average blood diastolic and systolic pressure. Contact pressures higher than 20000 Pa are considered a potential source of discomfort.

Under dynamic conditions, occupants of a vehicle suffer vibrations due to road roughness, wheel suspension, engine vibrations, etc. Among other multiple factors, these vibrations also depend on seat properties, since it may act as a damper. These vibrations may cause discomfort and damping properties of vehicle seats should be considered when assessing their comfort.

Multiple studies relate comfort and seat response under dynamic conditions (Seigler, 2002). Norm ISO 2631-1-1997 (ISO, 1997) describes relation between discomfort and vertical acceleration of a vehicle's occupant. This norm has been revised several times to adequate it to progress made in the field. Basically, tests aimed to evaluate dynamic comfort consist on analyzing the response of a seat specimen with an occupant model on it under the effect of a certain vibration spectrum. A relation has been established between discomfort and vertical vibrations of the occupant at a frequency range between 4 Hz and 8 Hz, because natural frequency of the assembly backbone-shoulders-head lies in this range (Chaffin, 1999). However, prolonged exposures to vibrations with smaller or higher frequencies may also cause discomfort.

Typical variables related to comfort assessment can be obtained from CAD-geometry of the assembly vehicle-seat-occupant or from the mechanical response of the seat at certain tests. Since these tests can be simulated numerically, comfort can be assessed in a CAD and analysis environment.

Moreover, the design of the car seat can be defined as a function of certain design variables in the same virtual environment. Design variables can be of two natures: geometric and material. The planned environment would contain a material database of a wide number of polyurethane foams. This database would contain the specification of the polymer required to manufacture the foam, as well as different material properties and mechanical properties. The design process will be significantly facilitated by means of this database, because of the capability of evaluating the performance of the same geometric design with different materials.

3. Numerical simulation of the static indentation test

As mentioned before, one of the objectives of the work described in this paper is the numerical simulation of the static indentation test over a seat cushion of polyurethane foam. To achieve this goal, two tasks must be done.

First, a previous fitting of the general material model for elastomeric foams to the particular case considered is required. Material properties of polyurethane foams can significantly change from one batch to another. For this reason, the existent material constitutive models for polyurethane foams are generic and some internal parameters must be fitted with results obtained from experimental tests, which must be made on the same foam batch as that of the simulation. Validation of this fitting is done by comparing results of these experimental tests with results of their simulations.

Once the material model for the polyurethane foam is calibrated, the simulation of the static indentation test can be performed by the Finite Element Method. Simulations presented in this paper were performed with ABAQUS/Standard and ABAQUS/Explicit (ABAQUS, 2006). Geometric nonlinearities due to large geometrical deformations were taken into account.

3.1 Material constitutive model

Flexible polyurethane foams are hyperelastic materials. They have certain properties, which make them very suitable to comply the seat function in vehicles, because they significantly contribute to attain comfort.

These foams can elastically undergo large strains, up to 90% in compression, and they have excellent energy absorption properties. They are highly nonlinear, since their stiffness largely depends on the strain level. This property has important consequences in the behaviour of the polyurethane foam cushions studied: under the loading of different occupants, or even under the loading of the same one seated in different ways, the seat cushion will respond with a different stiffness.

In addition, elastomeric foams have viscoelastic properties. However, as only static simulations were performed, no viscoelasticity is considered in the material model used in this work.

In elastomeric foams, a phenomenon of permanent energy dissipation in the first load cycles is observed. This phenomenon is called Mullins effect and causes material softening. In the present work, this effect was taken into account by fitting the material model with experimental measures of the fifth load cycle.

Mechanical properties of elastomeric foams depend on air humidity and air temperature. However, as tests described here are performed under constant laboratory conditions, no dependency on such variables is considered on the material constitutive model used.

The three main hypotheses in the mathematical modelization used for the mechanical behaviour of foams are isotropy at a macroscopic scale, hyperelasticity and non-hysteresis. Due to its manufacture process, elastomeric foams are actually anisotropic. However, as material orientation in the specimens for the simple tests is the same as in the seat cushions, isotropy assumption of the constitutive model is considered reasonable.

Ogden (Ogden, 1972) suggested a strain energy function for describing the behaviour of slightly compressible hyperelastic materials. This function was extended to highly compressible hyperelastic materials, such as polyurethane flexible foams (Mills, 2003). In (ABAQUS, 2006), this function is given as

$$U = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} \left[\tilde{\lambda}_1^{\alpha_i} + \tilde{\lambda}_2^{\alpha_i} + \tilde{\lambda}_3^{\alpha_i} - 3 + \frac{1}{\beta_i} \left((J^{el})^{-\alpha_i \beta_i} - 1 \right) \right] \quad (1)$$

being

N a parameter defining the approximation order of the model;

$\tilde{\lambda}_j$ principal stretch j ;

J^{el} elastic volume ratio and

α_i , β_i y μ_i material parameters, which depend on temperature, and which must be determined to fit the generic material model to the particular material case.

This material model is contained in the ABAQUS code (see *HYPERFOAM). The values of material parameters can be either directly specified or determined by means of a least square fitting from stress-strain measures of simple experimental tests. This second option is feasible because, for simple tests, an expression of stresses can be derived from Ogden function. To determine the parameters, the most suitable simple tests are those whose strain pattern and strain level are closely related to the tests to be later simulated with that material model. Properties of elastomeric foams can vary significantly from one batch to another. For this reason, in order to ensure coherence, simple tests should be performed over specimens of the same batch.

In the static indentation test to be simulated here, no important tensile stresses are expected, but compression stresses. For this reason, the parameters of the material model described were determined with experimental data of the uniaxial compression test.

3.2 Determination of parameters of the generic material model: uniaxial compression test.

In the uniaxial compression test, a regular parallelepiped specimen of base 0.1m x 0.1 m and 0.06 m high is used. The specimen is made of a polyurethane foam with a density of 44.7 kg/m³. The specimen is situated on a fixed plate and subjected to compression and decompression cycles under the action of a moving plate. Both plates must be parallel. On the fifth compression cycle, the load required to compress the specimen to certain strains is monitored, obtaining the compression load deflection curve of the material. The stress-strain pairs of data obtained are used to determine the parameters of the material model *HYPERFOAM in ABAQUS.

Moreover, the uniaxial compression test is simulated for checking purposes. A mesh of 10x10x6 8-node brick elements (C3D8) was used to discretize the specimen. The specimen is considered to be simply supported at its lower surface. The moving plate is modelled as a horizontal rigid surface. A contact has been declared between this surface and the specimen's upper surface with a friction coefficient of 0.75. Analysis is performed by prescribing a downwards movement of the moving plate.

In Figure 1, nominal strain – nominal stress curve obtained experimentally is shown. The shape of this curve agrees with the general strain-stress behaviour of elastomeric foams in compression. Three stiffness stages, which are related to the cellular character of foam, can be observed. First, for small compression strains (< 5%), cell walls bend and foam behaves linearly. At higher compression strains, columns formed by cell walls suffer elastic buckling and the slope of the strain-stress curve of the foam decreases. For high levels of compression strains, a densification of the foam occurs and its stiffness increases rapidly.

The points marked on the experimental curve of Figure 1, except the one related to nominal strain -0.05 were used for the parameter determination of the material model used in the numerical simulations.

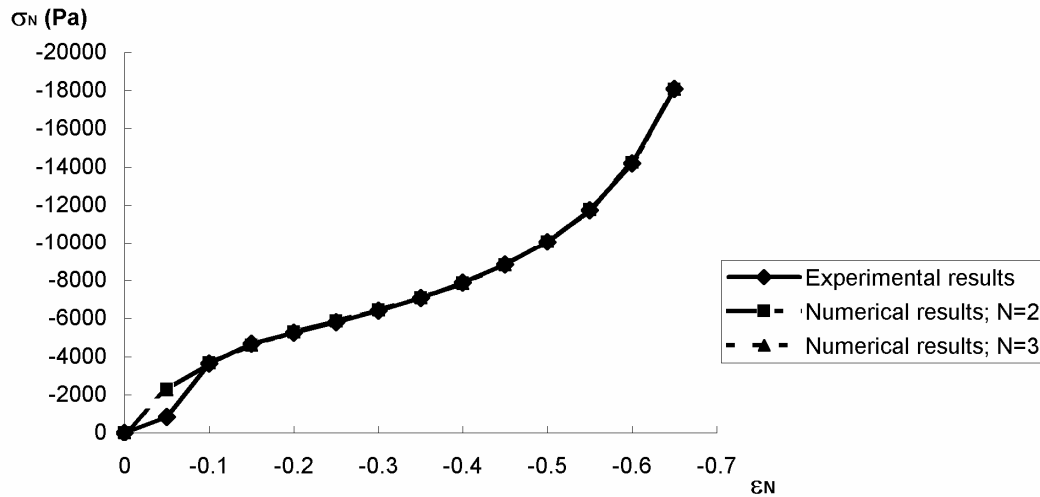


Figure 1. Uniaxial compression test: Comparison of experimental results and simulation results.

No value of the Poisson's coefficient could be deduced from experimental data. However, in a video of the uniaxial compression test, slight transversal strains are observed in the first load stages. This fact indicates that, at these stages, Poisson's coefficient does not vanish. No transversal strains are observed on further load stages. This implies that that Poisson's coefficient vanishes. In the parameter fitting of the material model, a constant zero value was assumed. This assumption seems reasonable, since in the indentation test large compression strains are expected.

Two order of approximations of the material model were considered (see Equation 1): $N=2$ and $N=3$. In order to verify the quality of the fitting, the nominal strain – nominal stress curves obtained in each simulation are also shown in Figure 1. The mean square error of the fitting is 0.74% for both cases. For simplicity, fitting with $N=2$ has been chosen for subsequent analysis. Fitting Ogden material model with $N=2$ for elastomeric foams is common in literature (Guerin, 2003) (Mills, 2003) (ABAQUS 2006b).

3.3 Static indentation test

Once the generic constitutive material model for elastomeric foams is particularized with experimental data of simple tests, more demanding tests, such as the static indentation test, can be simulated.

The aim of the static indentation test is to simulate the mechanical response of a seat cushion when an occupant seats on it. Results obtained in this test are useful for evaluating static comfort of the seat cushion.

This test is carried over a seat cushion positioned on a rigid support. A test form which reproduces the occupant thighs placed over the seat cushion. A vertical load is applied gradually on the test form, moving downwards on the seat cushion simulating the action of an occupant seating on it.

The penetration of the test form on the cushion is measured for certain loads applied to the test form. Initial relative position of test form with respect to seat cushion must satisfy certain rules.

Figure 2 shows the geometry of the seat cushion and of the test form, and the relative position of both parts at the beginning of the test.

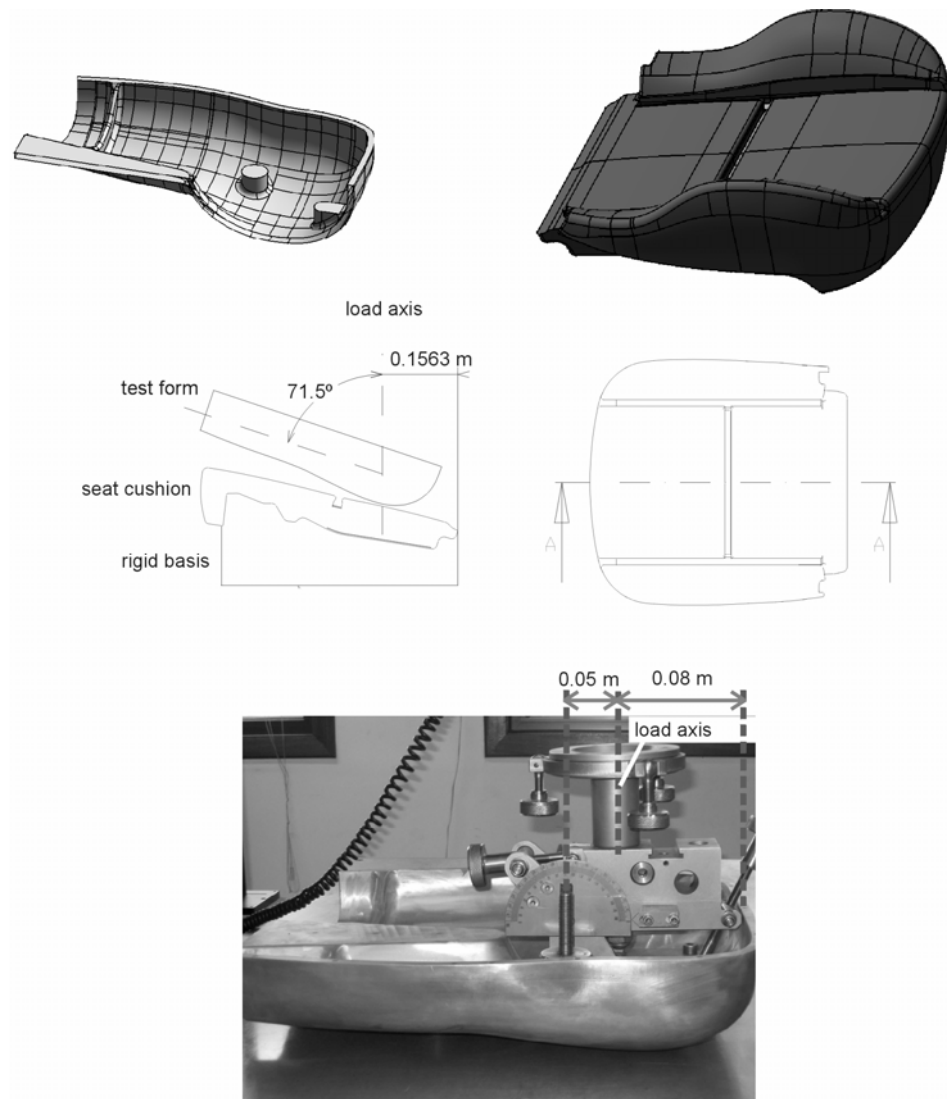


Figure 2. Geometry of seat cushion and test form

Seat cushion was discretized with 8-node brick elements (C3D8). In order to reduce computational time, only half of the seat cushion was considered in the finite element model, taking advantage of

symmetry with respect to XZ. Two finite element meshes with a different refinement degree have been considered. The coarser mesh (mesh A) has 14808 elements and 18183 nodes, while the finer mesh (mesh B) has 125164 elements and 138172 nodes. Both meshes are shown in Figure 3. Symmetry conditions have been prescribed at nodes at the symmetry plane and simply supported boundary conditions have been prescribed at the nodes attached to the lower base of the seat structure.

The test form was discretized with 1642 4-node rigid elements (R3D4). The reference node of the surface of the test form lies on the connection between test form and load axis. At this node, all degrees of freedom, except vertical displacement, are restricted.

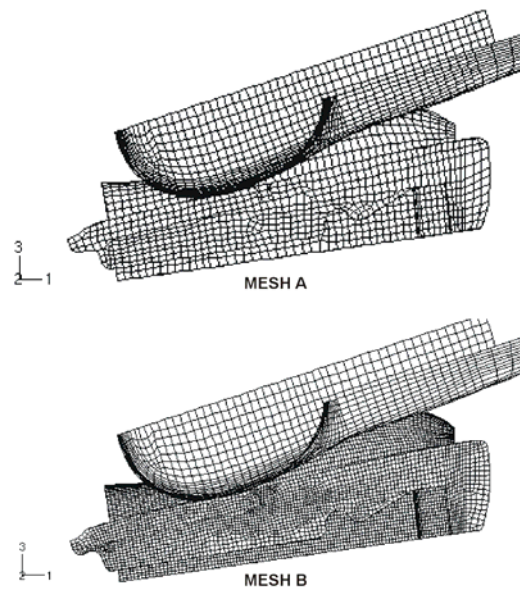


Figure 3. Static indentation test: Discretization of seat cushion and test form.

Due to the irregular shape of both seat cushion and test form, attention must be paid to adjust initial positions of the seat cushion and test form to agree with experimental test conditions. A contact has been declared between test form and seat cushion with a friction coefficient of 0.75. Moreover, self contact of the upper surface of the cushion has been declared with also a friction coefficient of 0.75.

In a HP workstation with a 2.8 GHz IntelXeon processor and 1.5 Gb of RAM memory, the computational time required for the simulation of indentation test with ABAQUS/Explicit was 0.5 hours for the model with the coarser mesh (mesh A) and 2 hours for the model with the finer mesh (mesh B).

Results obtained from the simulation of indentation test were validated with results of the experimental test. Figure 4 shows the curve applied load – vertical displacement of the test form obtained in the experimental test and also in the simulation.

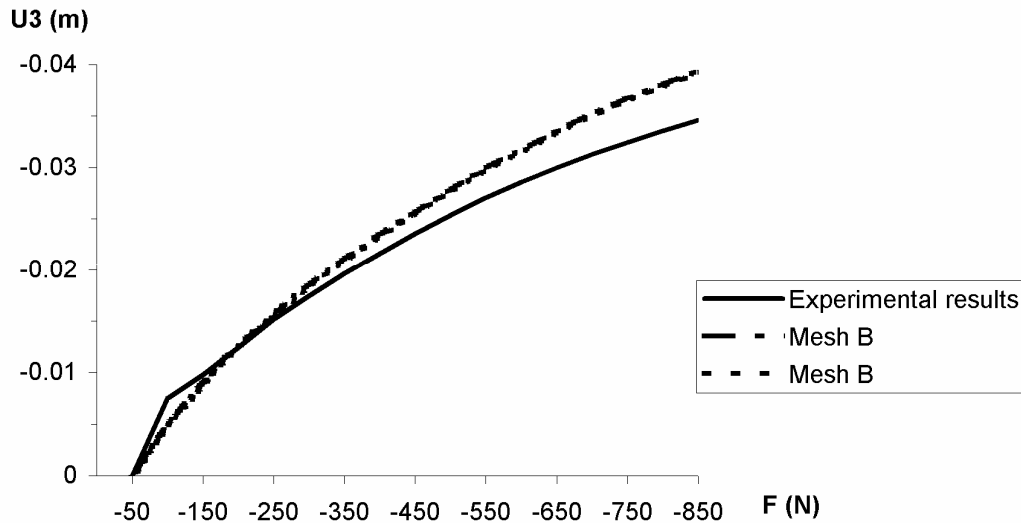


Figure 4. Static indentation test: Comparison of experimental results and simulation results.

As it can be observed, there is no significant difference between results obtained with mesh A and mesh B. However, as it can be observed, there is a discrepancy between results obtained in simulations and in experimental test. The displacement obtained numerically for a certain applied load is greater than the one obtained in the experimental test. Maximum relative error is 13% and it is obtained for the applied load of -850 N. Several causes can be the source of this discrepancy.

First, there are several uncertainties related to material modelization. This modelization was fitted with experimental data of the uniaxial compression test, but no information related to shear behaviour was introduced. Though compression is the prevailing deformation mode in the static indentation test, influence of shear behaviour may not be negligible a priori.

Another source of uncertainty is the fact that experimental results of the static indentation test were measured in the third load cycle. This has consequences on both material and geometry, since in the first load cycle permanent energy dissipation occurs. In the simulation, this fact has been taken into account in the material modelization, which was fitted with experimental data of the fifth load cycle of the uniaxial compression test. However, consequences on the geometry of the seat cushion have not been considered. Actually, in the second load cycle and following ones, the initial geometry of the seat cushion differs from that of the first load cycle. Thickness of the cushion under the test form diminishes after the first load cycle. This fact has not been taken into account in simulations, since for the third load cycle, initial geometry of first cycle has been considered.

The relevance of these facts with the grade of approximation of the curves in Figure 4 is a priori unknown and would require a deeper analysis.

A sensitivity study of the static indentation test with respect to friction coefficient between test form and seat cushion was made. Results indicated no significant sensibility for a range of Poisson's coefficient close to 0.75. A similar sensibility study was performed with the Poisson's ratio in a range close to 0.0. Results revealed no significant sensitivity on the applied load – vertical displacement curve.

From the experimental test, the only information available was the curve applied load – vertical displacement of the test form. However, from the simulation additional information can be easily obtained.

Figure 5 shows the vertical stress distribution (Pa) in the seat cushion (mesh A) when a load of -850N is applied on the test form. Pressure distribution on the lower surface of the seat can be relevant for the design of the basis where the seat is attached.

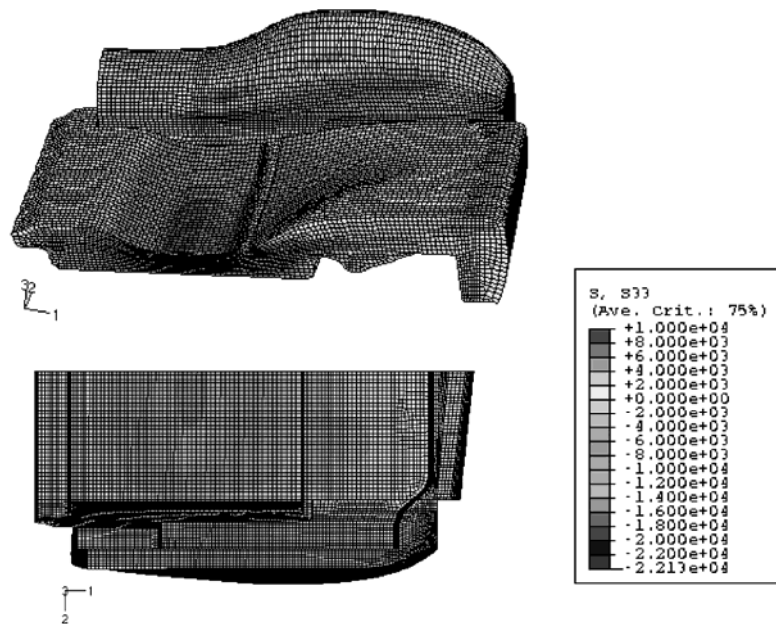


Figure 5. Static indentation test: Vertical stress distribution (Pa) in the seat cushion (mesh A) under an applied load of -850 N on the test form.

Contact pressures on the upper surface of the seat cushion and for different loads applied on the test form are shown in Figure 6. These pressures fields must be validated with experimental data measured with sensor blankets, but this information is not available. However, no significant differences are expected between numerical and experimental pressure fields, because indentation curve (see Figure 4) has a maximum relative error of 13%.

As mentioned in Section 2, contact pressure distribution is one of the most important issues when assessing comfort of car seats. Under an applied load of -850 on the form test, the maximum pressure obtained is 18000 Pa, which may be considered acceptable terms of comfort (Seigler, 2002).

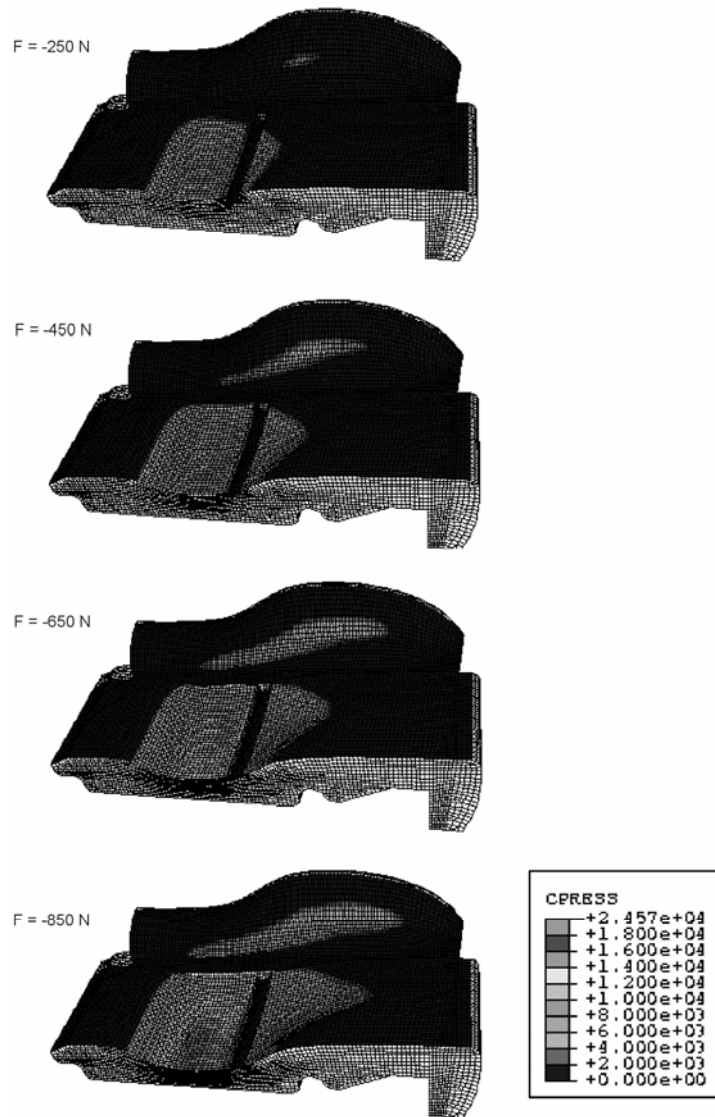


Figure 6. Static indentation test: Contact pressure (Pa) on the upper surface of the seat cushion for different applied loads on the test form.

In Figure 6, a progressive increase of the contact area related to an increase of the applied load can be observed. Distribution of this contact area is also relevant in terms of comfort. In Figure 7, the contact area is given as a function of the applied load. A differentiation is made between contact area on the seating plane and on the seat side wings. As expected, the larger contact area is that on the seating plane, which for an applied load of -850 N, represents a 79.2% of the total contact area.

Both seating plane and side wings contribute to the support of the occupant's load. Figure 8 shows the distribution of this load on the course of the test. For an applied load of -850 N, the seating plane supports 85.4% of it. The difference between the percentages of contact area and supported load for the same applied load lies in the fact that the supported force is related to the horizontal projection of the contact area on side wings (perpendicular to vertical reaction) and not to the contact area itself.

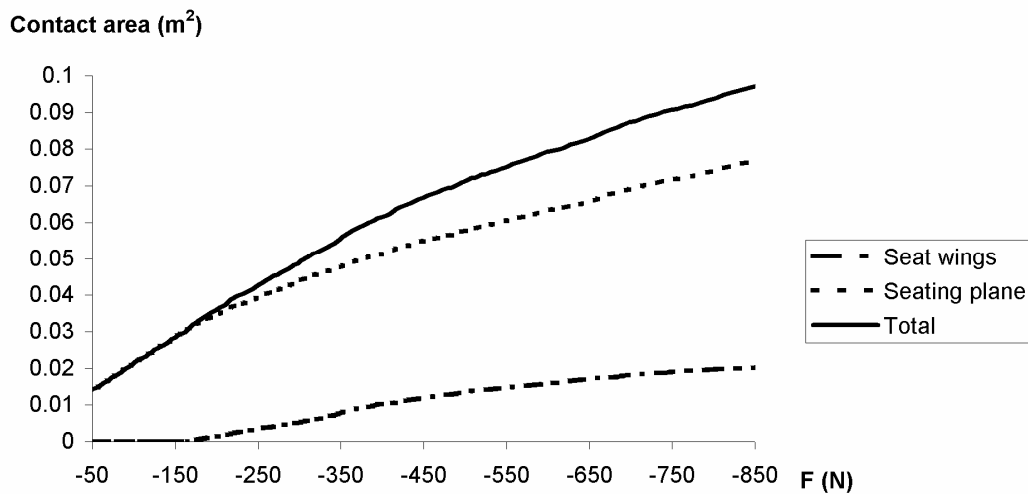


Figure 7. Static indentation test: Contact area (m²) as a function of the load applied on the test form.

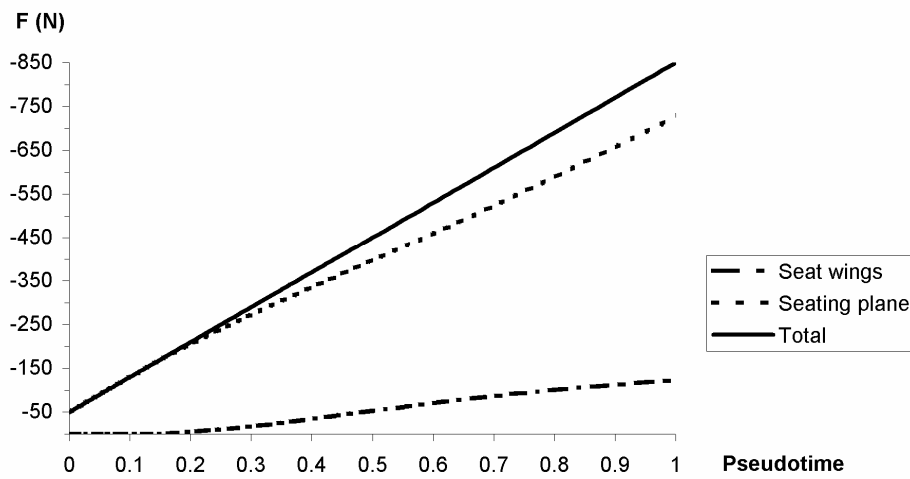


Figure 8. Static indentation test: Contribution of seating plane and side wings to the support of the load applied on the test form.

4. Conclusions and further lines of research

In the present paper, a feasibility study focused on the assessment of numerical simulations for comfort evaluation of car seat cushions made of flexible foam is presented. This study is a preliminary stage of a more ambitious program, which consists on the development of a virtual environment that integrates different tasks involved in design of car seats made of foam.

CAD-design, material databases of flexible foams and numerical simulations of tests aimed to assess comfort from the mechanical point of view are key modules in this virtual environment. Integration of design requirements and design variables in a same virtual environment reveals advantageous because of the capability to interact between them. This facilitates the assessment of consequences of a certain design change in a certain aspect of the seat performance. Moreover, numerical simulation of mechanical tests minimizes the number of specimens to be built, which contributes significantly to shorten the time required for a design loop. A large amount of work is still to be done to develop this virtual environment, both in the single modules and in the interface between them.

The work presented in this paper shows that expectations on the potential of the application of numerical simulations in comfort assessment are met. Experimental tests aimed to obtain results useful to compute comfort parameters can be successfully simulated numerically. Moreover, a great amount of information useful for comfort assessment can be easily obtained from these simulations. Positive impressions obtained in this preliminary study encourage to continue the development of a virtual environment for designing foam seats.

Further studies aimed to enhance performance of numerical simulation of the static indentation test should be done. Uncertainties in the material modelization of foams used should be studied.

For this purpose, further experimental tests should be performed. Volumetric compression test, for instance, could provide detailed information about Poisson's ratio. Moreover, in the numerical simulation of the indentation test, a better approximation of the initial geometry of the seat cushion at the beginning of the third load cycle should be considered.

In addition, simulation of dynamic tests aimed to assess dynamic comfort should be also considered. In this context, more complex material modelization may be required. Thus, viscoelasticity and Mullins effect should be taken into account. More complex occupant's models may also be required for comfort assessment under dynamic conditions.

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