DEVELOPMENT OF A SIMULATION MODEL FOR SANDWICH STEEL COMPOSITES BASED ON BEAM TEST DATA

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Abstract: This paper focuses on the development of a numerical model to simulate the structural dynamic behavior and perform vibro-acoustic properties identification for a steel composite beam with a sandwich structure. Steel sandwich structures, consisting of two steel thin plates with a visco-elastic layer in between, are known to display high damping properties and an enhanced absorption of the structure borne noise, thus actively contributing to environment protection. The validation was made by comparison with test data on a specimen of the same size and characteristics as the simulated model.

Key words: composite structures, steel sandwich structures, correlation and update

1. INTRODUCTION

The goal of this paper is the development of a numerical equivalent model to simulate the structural dynamic behavior and the vibro-acoustic properties identification for a steel composite beam with a sandwich structure, based on beam test data.

The steel sandwich structures materials, composed of two galvanized steel (or aluminum) sheets with a thin visco-elastic core layer in between, are known to display high damping properties and an enhanced absorption of the structure borne noise, thus actively contributing to environment protection. These properties are dependent of the thickness of the visco-elastic layer, and also of the temperature of the environment where the sandwich steel is used.

Sandwich materials are mostly used as a low-noise (sheet) structure in machine building, yacht building and ship building, hoppers, partition walls, floors, footbridges, pipeline insulation and numerous other applications. They also do not raise difficulties when used; they can be cut, drilled, punched or sawn like normal steel plates. Distorting operations, like bending, angle folding, and scoring, applied to the sandwich material also cause no problems if the sheets can move independently from one another. Mechanical connections can be applied without advance measures; welding and painting for protection also do not need special measures to be taken.

Also, the growing effort towards a better environment protection, against the pollution by noise, and also against the global warming, implies also a demand for the CO$_2$ emission reduction, and consequently for the vehicles weight reduction.

The steel sandwich materials started recently to be used for automotives components (in power train applications, such as transmission covers, oil pan and drive belt covers, but also as large size tailored parts to be used in structure, doors, hoods, a.s.o.), primarily for their damping and structure noise absorption properties in various temperature ranges, which are better than the properties of the classic steel that is regularly used, and in addition for reducing the overall automotives weight, hence their fuel consumption.

In order to determine the effect of the usage of new materials in a component’s design phase, the use of the finite element method as a simulation tool has become quite common, given the efficiency with which different properties and shapes changes impact on structures behavior can be evaluated. The accuracy of the results depends a lot on the accuracy of the model description, and consequently on the accuracy of the materials properties. For the “classical” materials, these properties were tested and confirmed. For newer materials, especially those formed by more than one component (composite materials in general, the steel sandwich structure presented above in particular), the overall properties need to be determined prior to their use in simulations.
In order to characterize the overall properties of a steel sandwich specimen, a number of equivalent models of the steel structure were developed and simulated, and the validation was made by comparison with test data on a specimen of the same size and characteristics as the simulated model. In the present paper, the selected simulation model and the properties identification process are described. The model that was simulated is similar in dimensions and layers distribution and thicknesses to the specimen that was tested. The purpose of the properties identification is their further use for a full model of a real part made of steel sandwich structure, studied under real loading.

2. PROPERTIES IDENTIFICATION PROCEDURE

The basic idea behind the properties identification procedure is that the core layer properties have an impact on different system dynamic properties, as follows:
- The shear modulus (G) of the core layer influences the system stiffness matrix \([K_i]\);
- The loss factor (\(\eta\)) of the core layer influences the system damping matrix \([K_i]\);
- The core layer density (\(\rho\)) is well known and therefore also the system mass matrix \([M]\).

The following dynamic system responses are available from the test results:
- Modal frequencies: \(\{f_{test}\}\),
- Frequencies response functions: \(\{FRF_{test}\}\).

These dynamic system responses can also be calculated with the finite element model:
- Modal frequencies: \(\{f_{FE}\}\), from the eigenvalues solution (SOL 103 in NASTRAN):
  \[
  \left(\{K_{Fe}\} - \omega^2 \{K_i\}\right)\{\psi\} = 0
  \]  \hspace{1cm} (1)
- Frequencies response function: \(\{FRF_{FE}\}\), from the forced response solution (SOL 111 in NASTRAN):
  \[
  \left(\{K_{Fe}\} + i\{K_i\} - \omega^2 \{M\}\right)\{X\} = \{F\}
  \]  \hspace{1cm} (2)

A two-step approach has been followed to identify the material properties:
- In the first step, the modal frequencies of the finite element model are aligned to the test ones, by tuning the shear modulus (G) of the simulation model;
- In the second step, the amplitude level at the resonance peaks of the simulation model computed response are aligned to the test ones by tuning the loss factor, expressed as damping (GE) of the core layer material in the simulation model.

Therefore, in order to have a set of updated properties for the core layer of a steel sandwich specimen to be used further in real application, the following are needed: to perform a test on the specimen, and to recreate in finite element simulation the test conditions and tune the simulation model until the computed results match the measurements. This sequence is called a correlation and update of the finite element model.

3. BEAM TEST PROCESS

By this test method, the vibration-damping properties of materials are measured: the loss factor (\(\eta\)), and Young’s modulus (E) or the shear modulus (G). The damping material’s modulus (either shear or Young’s) and loss factor can be measured with a single beam specimen vibrating in its several modes thus determining the properties as a function of frequency.

Brief description of the method [1]: the specimen of the desired configuration is clamped in a fixture and placed in an environmental chamber. Two transducers are used in the measurement, one to apply an excitation force to cause the test beam to vibrate, and one to measure the response of the test beam to the applied force. By measuring several resonances of the vibrating beam, the effect of frequency on the material’s damping properties can be established. By operating the test fixture inside an environmental chamber, the effects of temperature on the material properties are investigated. The material loss factor and modulus of damping materials are useful in designing measures to control vibration in structures and the sound that is radiated by those structures, especially at resonance. This test method determines the properties of a damping material by indirect measurement using damped cantilever beam theory. By applying beam theory, the resultant damping material properties are made independent of the geometry of the test specimen used to obtain them. These damping material properties can then be used with mathematical models to design damping systems and predict their performance prior to hardware fabrication. These models include simple beam and plate analogies as well as finite element analysis models.
The shape of the specimen used is sandwich structure beam, consisting of two steel sheets with a core of visco-elastic material in between, as shown in Figure 1. This specimen is used for determining the damping properties of the soft material of the core that will be subjected to shear deformation.

![Figure 1: Tested sandwich beam](image1.png)

The experimental setup uses a two channel spectrum analyzer and a random noise excitation signal, and is presented as a block diagram in Figure 2.

![Figure 2: Test setup](image2.png)

The frequency response of the beam is determined for the temperature in the environmental chamber. The analysis of test data provides also an estimation of the structure’s Young modulus and loss factor for each frequency peak in the measured frequency range at the given temperature. If the measurements are done at different environmental temperatures, a dependency of the Young’s modulus and loss factor of temperature is determined.

4. SIMULATION MODEL

Two models were developed in order to be computed with NASTRAN:
- A layered model with layers modelled with solid elements: two steel layers, each of two elements per thickness, and a thin core of polymer in between, all modelled in solid elements (PSOLID), as shown in Figure 3;

![Figure 3: Solid elements modelling of layers](image3.png)
A mixed shell and solid model, with a mixed modelling of layers: the two steel layers are modelled as shell elements (PSHELL), and the polymer core is modelled as one solid elements layer (PSOLID). For the shell elements, offset half-thickness values were defined in the appropriate directions, to match the real position of their middle surfaces. The mesh aspect and the offset scheme are represented in Figure 4.

![Figure 4: Mixed shell and solid modelling of layers: a) mesh aspect, b) offset of shell layers](image)

The steel layers thickness is 0.5 mm, the polymer core thickness is 0.06 mm.
The materials for steel and polymer core were defined for simplicity as NASTRAN MAT1 materials, with linear elastic behaviour. For the steel, the properties are standard: Young’s modulus $E=210000$ MPa, Poisson’s ratio $\nu=0.3$ and density $\rho=7.45e-9$ tons/mm$^3$. For the polymer core, initial values were used in calculation: for shear modulus $G=300$ MPa, Poisson’s ratio $\nu=0.4$, density $\rho=1.04e-9$ tons/mm$^3$. In order to have a model with elements of an acceptable quality, the element edge size is 0.5 mm.
The computation of the eigenvalues and the frequency response was done in NASTRAN for each model, in a simulation layout similar to the test setup: the specimen of dimensions similar to the tested part, clamped at one end, with the excitation and the receiver in the same positions. Unit excitation was used, and the response was calculated as velocities.
Given that the purpose of the properties identification is their further use for a full model of a real part made of steel sandwich structure, studied under real loading, the most “economical” model in terms of model size and computation duration was chosen for the study, and this is the one with mixed shell and solid elements.

5. TEST AND SIMULATION RESULTS

For the considered case, the scope is to identify the properties to be used in simulation at one temperature only (20°C), the response that was measured is a velocity, expressed in [dB(RMS)], and the Young’s modulus $E$ [MPa] and loss factor were estimated for each peak, depending only on the frequency. The results are presented in Figure 5.

![Figure 5: Beam test frequency response results](image)
The test results for the four identified peaks:
- Peak nr. 1: \( f_1 = 40 \) Hz, \( E_1 = 1.9 \times 10^{11} \) MPa, \( G_1 = 0.04 \);
- Peak nr. 2: \( f_2 = 200 \) Hz, \( E_2 = 1.9 \times 10^{11} \) MPa, \( G_2 = 0.01 \);
- Peak nr. 3: \( f_3 = 580 \) Hz, \( E_3 = 1.9 \times 10^{11} \) MPa, \( G_3 = 0.011 \);
- Peak nr. 4: \( f_4 = 1100 \) Hz, \( E_4 = 1.9 \times 10^{11} \) MPa, \( G_4 = 0.015 \).

The first step was to tune the shear modulus \( G \) for the simulation model in order to get the same peaks as in test. As it is visible from the test data, the value of \( G \) is not the same along the studied frequency range (1 to 1500 Hz). This created a difficulty in obtaining the simulation results, given the fact that it is not possible to define frequency dependent shear modulus in NASTRAN property cards. The solution was to define NASTRAN setups for smaller frequency ranges (0 to 350 Hz, 350 to 875 Hz, 875 to 1500 Hz), and tune the shear modulus \( G \) for each of these intervals to align the simulation peaks with the test peaks.

The result of the tuning of frequency peaks is summarized in Table 1.

<table>
<thead>
<tr>
<th>Test results</th>
<th>( G=270 ) MPa</th>
<th>( G=320 ) MPa</th>
<th>( G=370 ) MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq.[Hz]</td>
<td>Freq.[Hz] %</td>
<td>Freq.[Hz] %</td>
<td>Freq.[Hz] %</td>
</tr>
<tr>
<td>200</td>
<td>199.9 0.0</td>
<td>201 0.4</td>
<td>202 0.7</td>
</tr>
<tr>
<td>580</td>
<td>571 -1.6</td>
<td>580.1 0.0</td>
<td>584 0.7</td>
</tr>
<tr>
<td>1100</td>
<td>1070 -2.7</td>
<td>1090 -1</td>
<td>1101 0.1</td>
</tr>
</tbody>
</table>

In the second step, the loss factor was also tuned for the defined frequency ranges, the resulting values being 0.10, 0.12 and 0.18.

With the mentioned shear modulus and loss factor values for the intervals, the aggregated post-processed frequency response obtained with the mixed shell and solid elements model is represented in Figure 6. By comparing these simulation results with the test results in Figure 5, note that the correlation of both frequency and amplitude of test and simulation peaks is good.

Table 1: Frequency peaks tuning

Figure 6: Simulation frequency response results
6. CONCLUSION

The paper presented the development of a numerical model to simulate the structural dynamic behaviour and the vibro-acoustic properties identification for a steel composite beam with a sandwich structure. Steel sandwich structures, consisting of two steel thin plates with a visco-elastic layer in between, are known to display high damping properties and an enhanced absorption of the structure borne noise. An equivalent model was presented, a mixed simulation and experimental properties identification procedure was presented, and the properties were identified by correlation with test data obtained on a specimen of the same size and characteristics as the simulated model. A good correlation between test and simulation results can be observed by comparing the test results in Figure 5 with the simulation results in Figure 6. Therefore, the identified core layer properties (values of the shear modulus and loss factor in the defined frequency ranges) and the studied modelling approach (the representation of the steel sandwich structure as a mixed shell and solid elements model) are appropriate to be used for full models of real parts made of steel sandwich structures, studied under real loading conditions.

7. REFERENCES