Quiet Steel® Body Panel Design with DAMPÒ - A Custom Preprocessor Utilizing MSC-PATRAN/NASTRAN

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ABSTRACT

Quiet Steel®, a laminated metal, integrates vibration damping into the main structure of the vehicle. This allows for the reduction or elimination of sound absorbing materials and mastics in the conventional noise solution. With laminated metal, the result is a noise, vibration, harshness improvement without adding weight and cost. However, the marked difference between the stiff steel laminate skins and the soft laminate adhesive core requires a three-layer mesh to capture the resulting through-thickness shearing. A finite element preprocessor, DAMP®, eases the design process by creating the three-layer representation, directly from a sheet metal mesh. DAMP® utilizes both MSC.Patran [1] and MSC.Nastran [2] parameters in the mesh generation process. DAMP® is demonstrated here with the design of a front floor panel. The laminated panel is analyzed to determine its proper gauge to maintain the stiffness of the sheet metal original. A modal test is also simulated to demonstrate the reduced vibrations associated with the Quiet Steel® design.

INTRODUCTION

Quiet Steel® is emerging as the material of choice in optimizing sound packages in automotive body applications. By adhesively bonding two flat pieces of sheet metal together in a continuous coil process, this production friendly laminate gives the automotive engineer the design flexibility of integrating vibration damping within the main structure of the vehicle. Noise transmission abatement is also available with a Quiet Steel® design. Testing has shown the laminate performs as well as, or better than, a steel/mastic solution [3]. The Quiet Steel® design therefore allows for the reduction or elimination of sound absorbing materials and mastics in the conventional noise solution. The bottom line advantage of using this laminate is a noise, vibration, harshness (NVH) improvement while reducing weight and cost to the vehicle.

While achieving benefits in sound quality, the design analysis of these parts is challenging due to the marked difference in material properties of the laminate layers. Any analysis is difficult because, under deformation, through-thickness plane sections do not remain plane. The adhesive layer is so soft that the two layers of steel slide against each other quite readily, as shown in Figure 1. This shearing activates the main damping mechanism of the laminate. It also allows for the laminate to be formed into many complex contoured shapes. However, when modeling these materials, this deformation requires a detailed three-layer model to capture this shearing effect. To further complicate the analysis, the adhesive material properties are temperature and frequency dependent. These design challenges were the motivation for DAMP®, a finite element preprocessor for designing laminated metal components. DAMP® eases the design process by generating all analysis input for laminated components, allowing the engineer to concentrate more on the laminate design benefits.

DAMP® has been tailored to use MSC.Nastran conventional elements to describe the laminated design. It builds a three-layered element model from an original shell element MSC.Patran neutral file of the mesh. The resulting three-layer mesh can be used for any standard MSC.Nastran investigation of the part. Here, static displacements are determined to gauge an equivalent stiffness front floor panel to the steel original. The design is analyzed as connected to a rear steel floor panel. Connectivity in an assembly further demonstrates the flexibility of the laminate representation. MSC.Nastran is also used to show the greatly damped vibrations associated with the Quiet Steel® design. This paper demonstrates the procedures of how a design engineer can proactively create a vibration damped noise/vibration solution, while achieving equivalent stiffness to the original solid metal design.

THE FINITE ELEMENT PREPROCESSOR, DAMP®

Laminated metal damps vibrations by the cyclic shearing of its core adhesive layer, between the two layers of steel skins. The finite element model of a laminate design must contain all three layers of material to capture this shearing action. One of the simplest idealizations for the three layers is the offset shell element and solid element model [4] as shown in Figure 2. The offset shell elements represent the steel layers of the laminate, while the solid elements represent the core adhesive. Offset shell elements are essential for the laminated metal description. MSC.Nastran was the first (of only two) finite element packages to contain offset shell elements. The offset shell elements are defined away from their mid-plane, so that they lie at the top and bottom of the adhesive core. This allows for the elimination of two rows of nodes that would normally be needed if conventional shell elements were used. In addition, the thickness of the laminated metal skins can be changed, without generating a new geometry, with the use of offset shell elements. This allows for the skin thickness of the laminate to be altered, without having to construct a new mesh. Conventional shell elements would require new grid locations to define the new mid-plane for any thickness changes. Offset shell elements require only a change of element parameters to change the skin thickness of the laminate.

While this three-layer design is easy to envision for a flat part, a further challenge lies in applying the representation in a complex contoured design. This is where DAMP® [5-9] becomes essential to the design process. DAMP® generates all laminate parameters necessary for design. First, a conventional shell element mesh is made of the part. Next, MSC.Patran is used to orient all element normals in the same direction. Then, a MSC.Patran neutral file of the mesh is created for the design. DAMP® reads in the neutral file and, essentially, duplicates each element, an adhesive layer away from their original location. DAMP® converts every element into a bicubic surface, determines the local normal, and then translates the element the adhesive thickness, down this normal [8]. At this lower interface, the surfaces are intersected, so that curvature of the original design is preserved. If the elements do not intersect (due to the original curvature of the part) DAMP® will expand the elements first, then translate, and try the intersection again. The two layers of surfaces are then identified as offset shell elements. The resulting two layers of shell elements are then connected with solid elements. DAMP® preserves the original numbering sequence of the elements and nodal points, increasing each element and node number by a constant value to identify the new surface. This easily identifies the grids of the solid elements. Number preservation also makes applying loads, boundary conditions, and multi-point constraints easy, once they have been defined in the original model. A laminate model for a front floor pan is shown in Figure 3. The inset in Figure 3 shows the two layers of shell elements and the interconnecting solid. A consequence of the mesh is that extreme aspect ratios result for the core layer. Yet, good correlation has been achieved with experimental results [7,9].

DAMP® also determines the core material properties from internal material models. The material properties of the adhesive core are temperature and frequency dependent. Core material models were determined from a standard vibrating beam test. These models can be used to determine material property estimates for static and dynamic conditions. For the stiffness calculations, a low frequency, 150 Hz, modulus is used. The low frequency mimics the static state. For the dynamic calculations, a constant modulus and material damping were identified at 250 Hz. These properties are representative of frequency ranges less than 500 Hz. All material properties were defined at room-temperature conditions. The generated finite element model and the 150 Hz material properties will be used in the following to gauge the laminated floor pan to maintain the stiffness of the original steel part. The alternate material properties at 250 Hz will be used to demonstrate the natural frequencies, mode shapes, frequency response, and damping of the laminated design.

DESIGNING A QUIET STEEL® BODY PANEL – FRONT FLOOR PAN

STIFFNESS CALCULATION:

The front floor pan is analyzed as part of a larger assembly that includes the rear floor pan. The full assembly is shown in Figure 4. The parts are joined together with multi-point constraints at the weld points between the two parts. These locations are indicated in the figure by small circles. The boundary of the entire floor pan is pinned in position. In addition, in order to more closely mimic the in-service condition, the floor is pinned along the regions of supporting cross members. The laminate is then analyzed to maintain the same stiffness as the original steel construction. This is done by examining the displacement due to a static load. Four loading positions were selected. These locations are indicated by the numbers in Figure 4. Having calculations at various locations gives a good representation of the local stiffness seen with the laminate construction. A 1N load is applied, equally split among four nodes, perpendicular to the surface at every location.

The laminate stiffness calculations were made with the offset shell/solid model as described above. The skin thickness was varied until approximately the same displacement was given from the laminate and steel designs. Maximum displacements for each load case are given in Table 1. Also shown in the table is the resulting weight for each panel. Some laminates are labeled not used to indicate their calculations were not necessary to judge the equivalent laminate.

Table 1: Front Floor Displacements and Weights.

Material	Displ. at pt. 1 (mm)	Displ. at pt. 2 (mm)	Displ. at pt. 3 (mm)	Displ. at pt. 4 (mm)	Weight (lb)
steel sheet 0.91mm (0.036")	2.00E-03	4.36E-03	3.91E-03	1.01E-02	33.63
lam. skin thick. mm (in)					
0.5588 (0.022)	2.59E-03	**4.29E-03**	4.94E-03	1.20E-02	
0.5842 (0.023)	2.31E-03	3.94E-03	4.45E-03	**1.08E-02**	43.29
0.6096 (0.024)	**2.07E-03**	3.63E-03	**4.02E-03**	9.67E-03	
0.635 (0.025)	1.86E-03	3.36E-03	3.65E-03	8.73E-03	
0.6604 (0.026)	1.68E-03	3.12E-03	Not used	not used	

Note: All laminates have steel skins and 0.0254mm (0.001") core. Displacement equivalents for 1N load are in bold. Weight of laminates is also indicated.

While each loading condition may give preference to a different thickness, viewing the results in Table 1 will show the 0.5842mm (0.023") skin thickness laminate to most closely match the stiffness of the baseline floor pan part, by providing a comparable average stiffness.

The resulting laminate thickness for equivalent stiffness is greater than the original steel thickness. This is due to the low modulus of the adhesive material at this temperature and frequency (low frequency mimics static state). The low modulus allows the layers to slide against each other, decreasing the stiffness of the laminate. If a considerable amount of welds are present, or extensive supporting structure, it may be possible to use a thinner laminate. This extra local support will not effect the damping of the laminate, unless it inhibits the overall shearing of the laminate. The design engineer will have to weigh several factors in the final gauge selection, from tooling to noise abatement. However, noise transmission abatement will benefit greater from a thicker laminate.

NATURAL FREQUENCIES AND MODE SHAPES:

All dynamic characteristics were determined with the boundary conditions shown in Figure 4. These conditions represent a modal test on the front and rear component, detached from other pieces, but fixed in position. The offset shell/solid model was used for the laminate as described above. Material properties for the skins of the laminate were those used for the original steel design. Material properties for the polymeric core were determined by the preprocessor at 250 Hz and 24°C (75°F). Ideally, the natural frequencies for the laminate design should be calculated with a modulus at that same frequency. The laminate values are then just estimates of the actual value. Table 2 gives the floor natural frequencies of the steel (0.91mm for both front and rear panels) and laminate/steel (0.5842mm - or 0.023” skins, 1.19mm total, or 0.047” total for front floor, 0.091mm steel for the rear) designs.

Table 2: Natural frequencies of steel and laminate/steel floor designs (in Hz).

Mode	Steel 0.91mm (0.036”) Front and Rear	Laminate/Steel Laminate Front: 0.5842mm (0.023”) skin-1.19 mm (0.047”) total Steel Rear: 0.91mm (0.36”)
I	71.94	70.98
II	97.72	96.6
III	101.52	98.03
IV	102.55	98.76
V	104.48	102.3
VI	106.71	106.71
VII	118.3	117.52
VIII	125.23	121.45
IX	128.3	121.66
X	132.4	125.22

Selected mode shapes of the corresponding vibrations are shown in Figure 5. Mode shapes will change with other boundary conditions, or if other parts are connected to the designs. The situation here is of a modal test on the floor alone, with the components fixed in position.

FREQUENCY RESPONSE AND DAMPING:

Frequency response calculations were done at 24°C (75°F) from 0-350 Hz at 0.625 Hz increments using a modal steady state dynamics solution (SOL 111). The steel design was given a loss factor of 0.002. The laminate calculations were made with the core material properties for 250 Hz. This corresponds to the same values used in other laminate analyses [5,6]. A harmonic load was applied at location 2 in Figure 3. The acceleration was then monitored at location 3 of Figure 3. Predictions were made for the 0.91mm (0.036") steel floor and the 0.5842mm (0.023") skin laminated (1.19mm total, or 0.047") front floor, with same steel rear (0.91mm). The resulting frequency response is shown in Figure 6. As can be seen, the laminate responses are greatly damped as compared to their steel counterparts. A detailed modal analysis of this frequency response curve would give the damping of the laminate. This type of analysis could separate out the extremely damped peaks in the portions of the curve beyond 150 Hz. Simple calculations can be used to determine the level of damping in the first peak.

A technique known as the 3dB method will give the level of damping [10]. The 3dB method determines the damping value, or loss factor, from a ratio of the width of the peak to the peak frequency ($\Delta f/f$). The width is taken at $1/\sqrt{2}$ (~2/3) of the peak acceleration amplitude. For any steel (or any metal) design, without considering damping due to connections with other parts (system damping), the loss factor is ~0.002. If one considers system damping, a steel design has a loss factor of ~0.01. Using the 3dB method, the loss factor for the first peak (97 Hz) of the laminate design is 0.0763. A loss factor better than 0.07 is considered well damped. Beyond 150 Hz, damping will be greater than 0.1.

CONCLUSIONS

A finite element preprocessor, DAMP®, has been presented as well as its use in designing laminated metal body parts. DAMP® utilizes MSC.Nastran and MSC.Patran parameters in converting a conventional shell element model of a body panel into a three-layer, offset shell/solid mesh, representative of a laminated metal design. The resulting mesh can be used for any conventional finite element analysis available in MSC.Nastran.

With this preprocessor, a Quiet Steel (vibration damped steel) floor pan was analyzed to determine the appropriate laminate gauge to maintain the stiffness of the original sheet metal design and to demonstrate its dynamic characteristics. The front floor was analyzed as connected to a steel rear floor pan. With the three-layer configuration, material properties for the laminate are defined for the base material in each layer, the adhesive core and the steel skins. Static and dynamic calculations showed the following results:

- To maintain equal stiffness, the 0.91mm (0.036") steel front floor pan should be replaced with a laminate constructed of equal thickness skins measuring 0.5842mm (0.023", total laminate thickness 1.19mm, or 0.047").

- The natural frequencies of the equivalent stiffness laminated design are very close to the original steel design. Natural mode shapes are particular to the pinned boundary conditions applied in this analysis.
- The laminated frequency response curve is considerably damped as compared to the steel original. A damping value, or loss factor, of 0.076 was determined for the first peak of the frequency response curve, with values better than 0.1 for the rest of the curve. A maximum loss factor of 0.01 is available from the steel design (considering system damping). A loss factor of 0.07 is considered well damped. This implies that the laminated steel is ideal for this design application in combating noise due to vibration.

In addition, the following can be stated:

- Stiffness calculations were made without supporting structure in the analysis (only mimicked with pinned boundary conditions). These additions may reduce the shearing between layers of the laminate and stiffen local sections. Therefore, the gauge of the laminate here is conservative (thick).
- Welding will not effect the damping of the laminate, unless so much is added that it inhibits the shearing of the laminate.
- Dynamic analysis has shown how the laminate damps vibrations for only one set of boundary conditions. These conditions may not reflect the actual situation, but give a relative view of the laminate's ability to damp vibrations.

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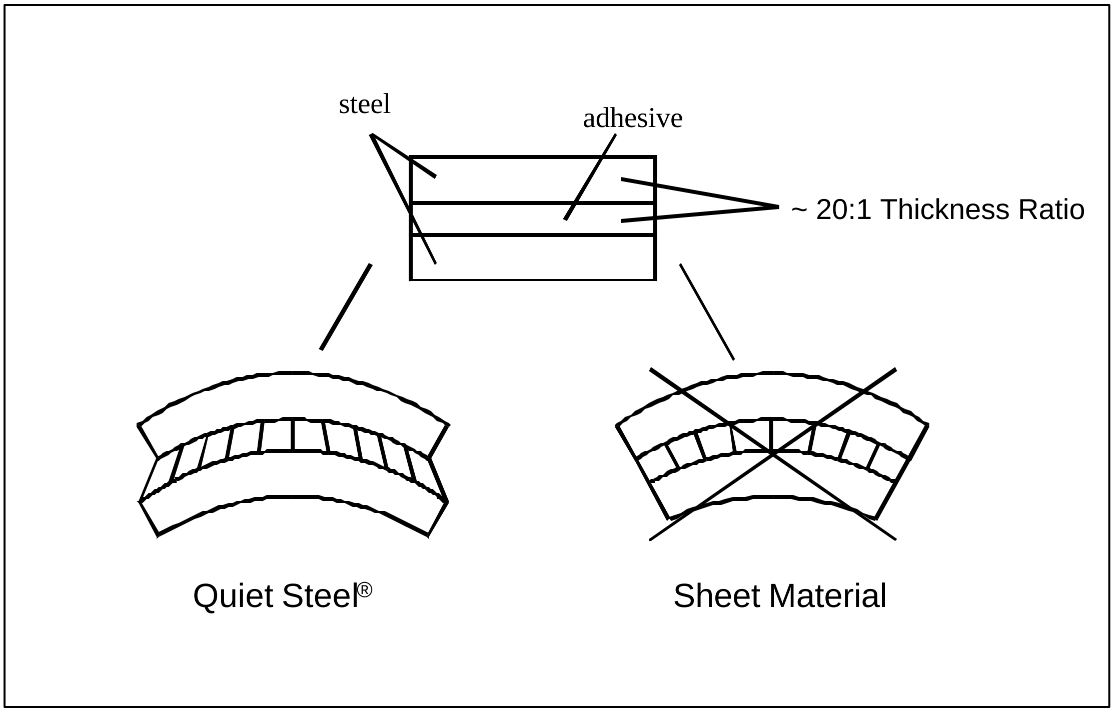

Figure 1: Through-thickness shear deformation pattern associated with the Quiet Steel®, or laminated metal, design as opposed to that of a sheet material.

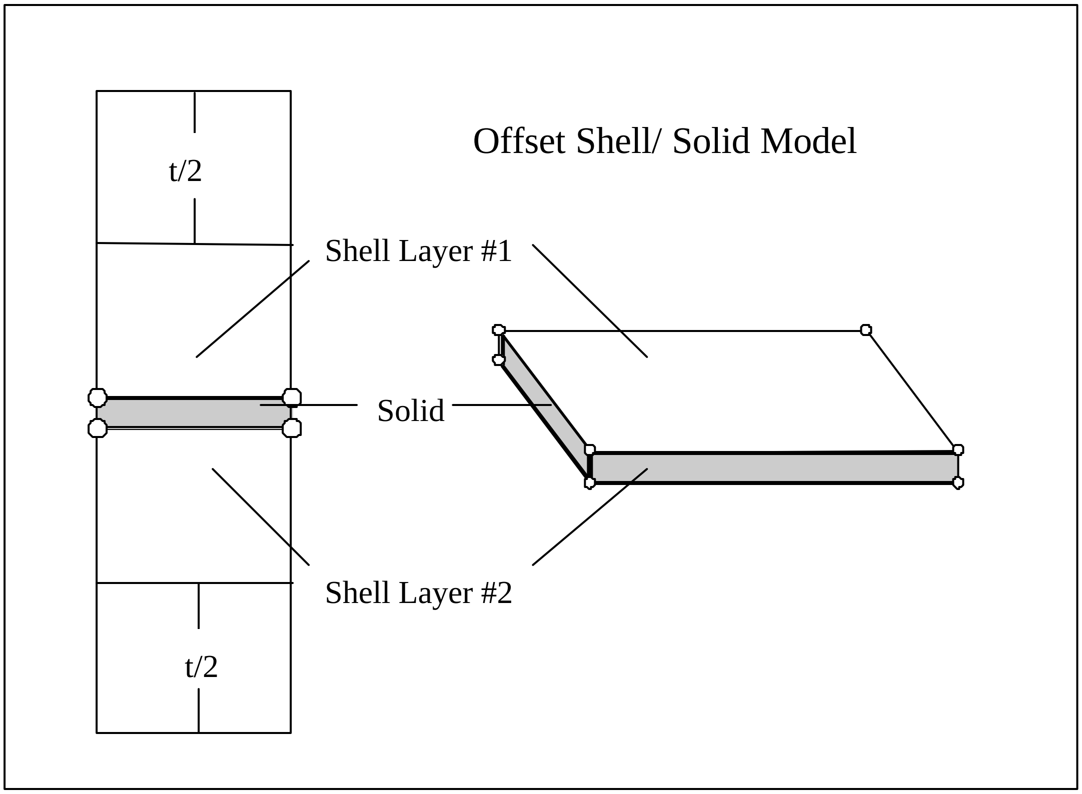

Figure 2: Finite element representation of laminated metal. Steel laminate skins are modeled with offset shell elements. Adhesive laminate core is modeled with solid elements.

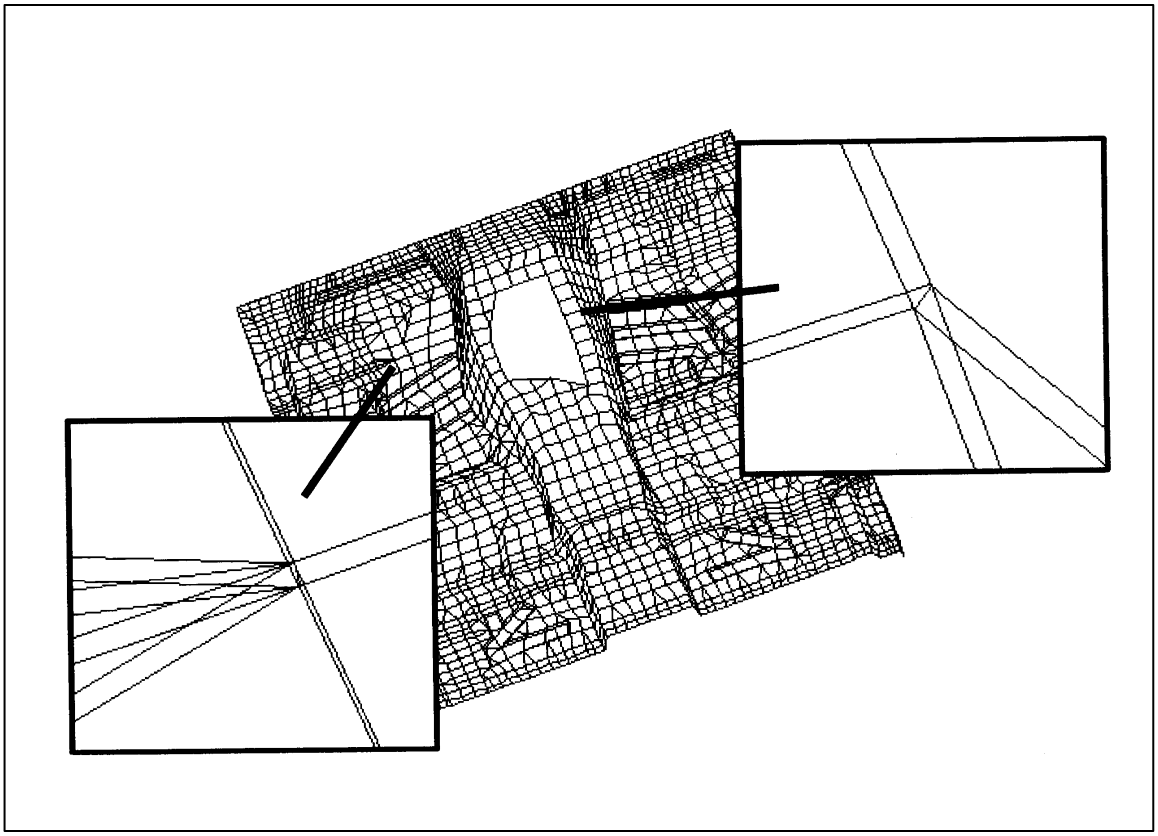

Figure 3: Laminated mesh of front floor pan

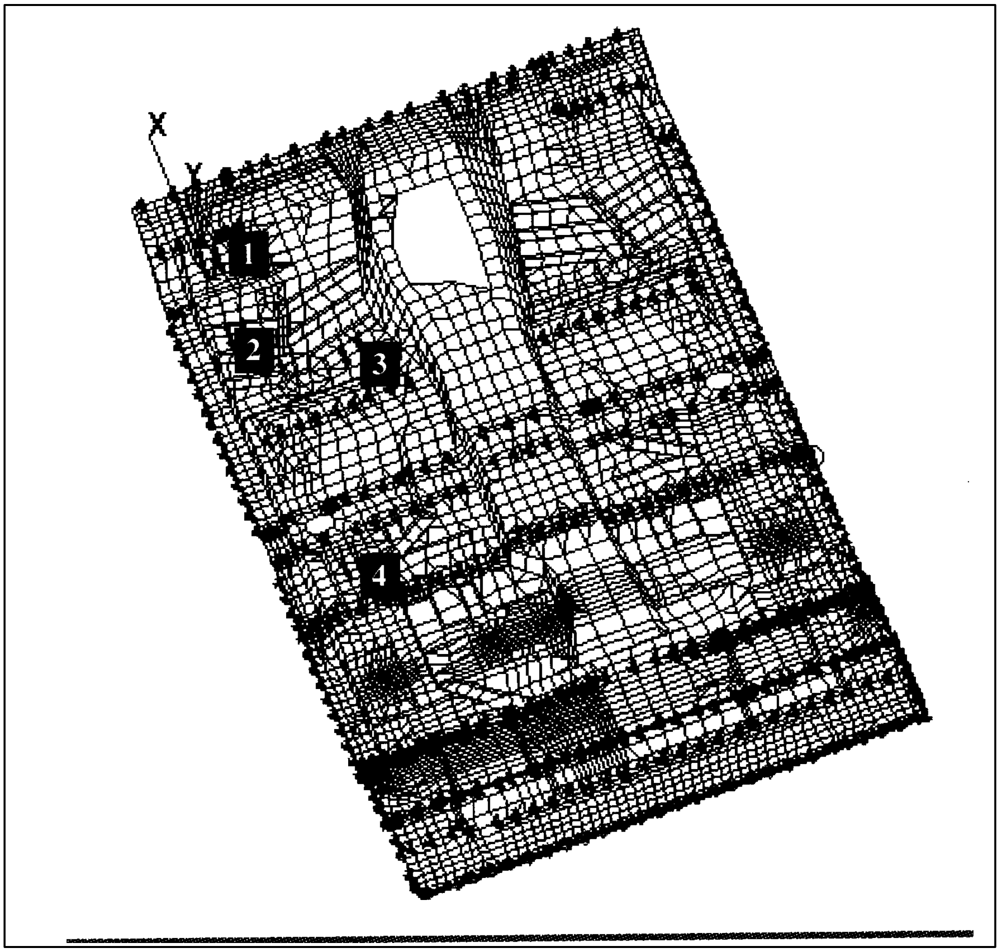

Figure 4: Loading and monitoring points for the static and frequency response analysis.

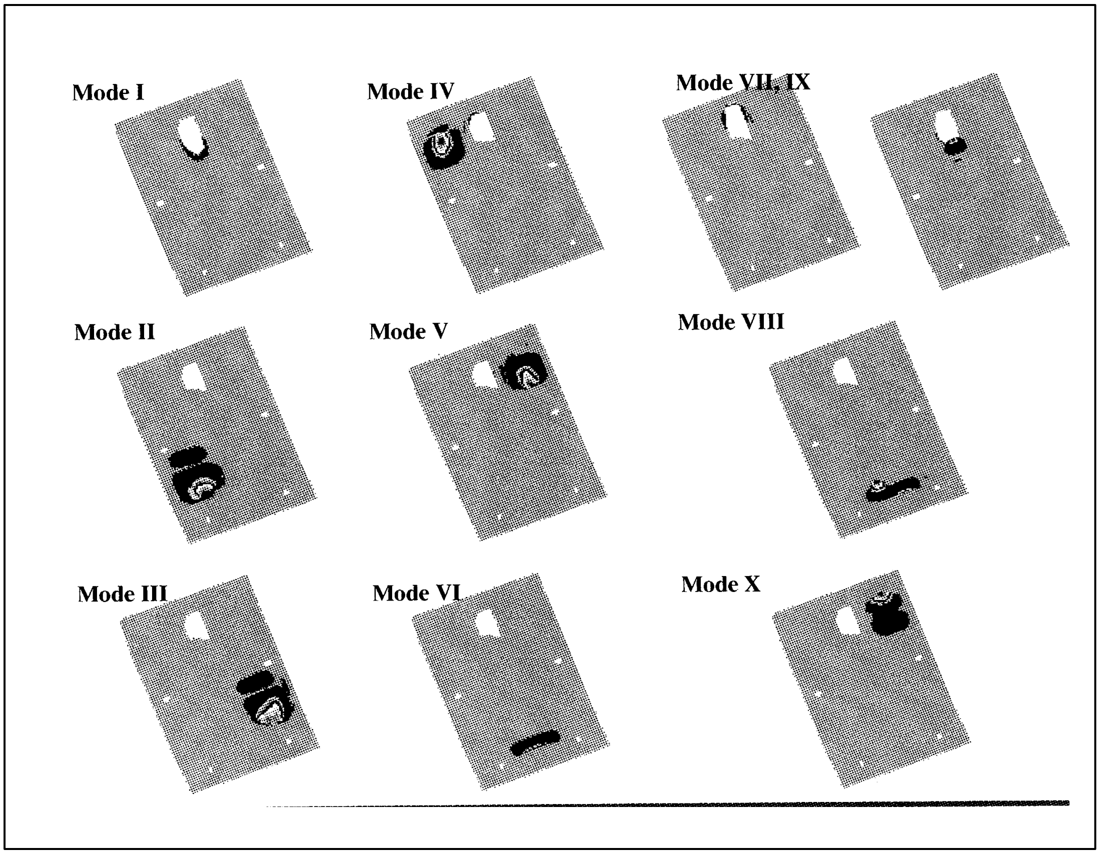

Figure 5: Selected mode shapes of the floor pan

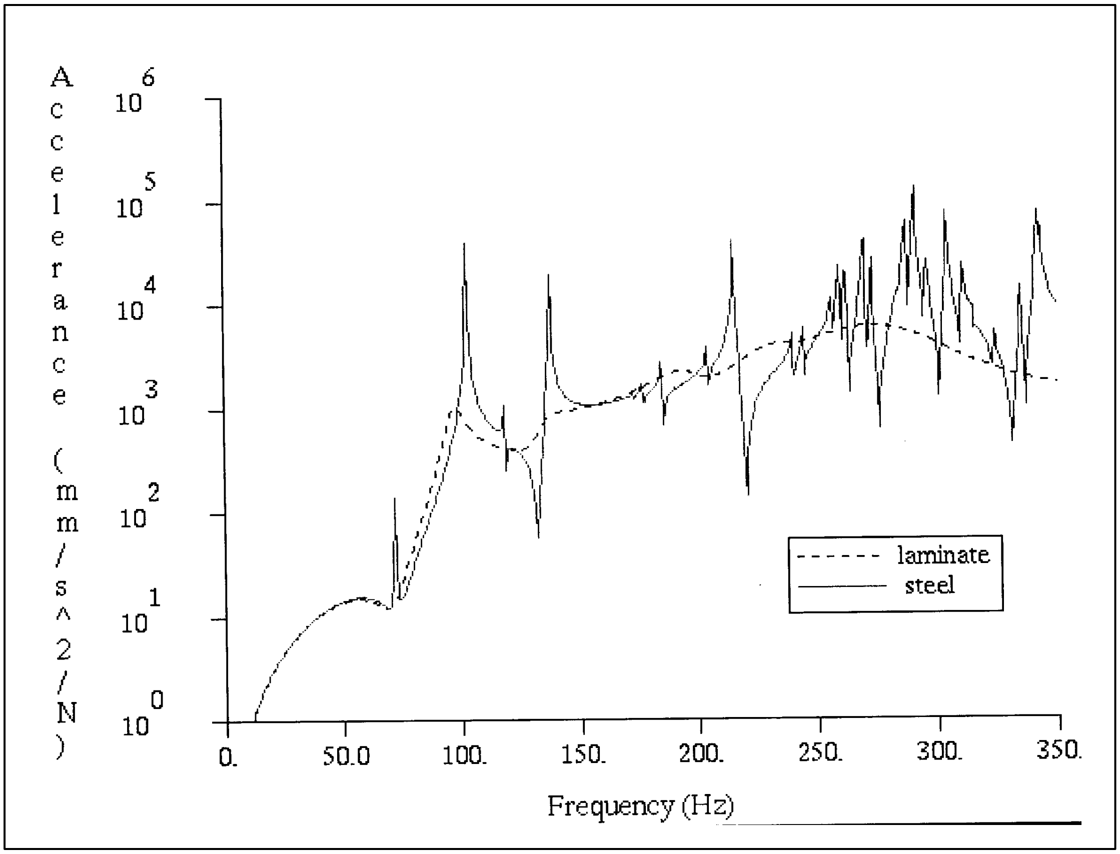

Figure 6: Frequency response from laminate and steel front floor.