Influence of the Loading Position on a Honeycomb Sandwich Using Nonlinear Analyses

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This paper presents the influence of the position of an applied static load on a honeycomb sandwich with core made of resin impregnated honeycomb and caps made of epoxy resin. The nonlinear analyses were concentrated underneath the area of applied force and on the side of one wall of the honeycomb. The results obtained can be used to determine the effect of a small area impact on a honeycomb sandwich or to establish the stress distribution pattern during compression tests on the walls of a cellular structure.

Keywords: honeycomb, sandwich, nonlinear, resin impregnated paper, epoxy resin.

Honeycomb structures

Honeycomb structures are natural or man-made structures that have the geometry of a honeycomb to allow the minimization of the amount of used material to reach minimal weight and minimal material cost. The geometry of honeycomb structures can vary widely but the common feature of all such structures is an array of hollow cells separated by thin vertical walls. The cells are often columnar and hexagonal in shape. A honeycomb shaped structure provides a material with minimal density and relative high out-of-plane compression properties and out-of-plane shear properties.

Man-made honeycomb structures are manufactured by using a variety of different materials, depending on the intended application and required characteristics, from paper or thermoplastics, used for low strength and stiffness for low load applications, to high strength and stiffness for high performance applications, from aluminum or fiber reinforced plastics. The strength of laminated or sandwich panels depends on the size of the panel, facing material used and the number or density of the honeycomb cells within it. Honeycomb composites are used widely in many industries, from aerospace industries, automotive and furniture to packaging and logistics. The material takes its name from its visual resemblance to a bee's honeycomb - a hexagonal sheet structure [1].

Nonlinear calculus

For nonlinear problems, the stiffness of the structure, the applied loads, and/or boundary conditions can be affected by the induced displacements. The equilibrium of the structure must be established for a deformed shape which is unknown and must be guessed. At each equilibrium state along the equilibrium path, the resulting set of simultaneous equations will be nonlinear. Therefore, a direct solution will not be possible and an iterative method will be required.

Several strategies have been devised to perform nonlinear analysis. As opposed to linear problems, it is extremely difficult, if not impossible, to implement one single strategy of general validity for all problems. Very often, the particular problem at hand will force the analyst to try different solution procedures or to select a certain procedure to succeed in obtaining the correct solution (for example, "Snap-through" buckling problems of frames and shells require deformation-controlled loading strategies such as displacement and arc-length based controls rather than force-controlled loading). For these reasons, it is imperative that a computer program used for nonlinear analyses should possess several alternative algorithms for tackling wide spectrum of nonlinear applications. Such techniques would lead to increased flexibility and the analyst would have the ability to obtain improved reliability and efficiency for the solution of a particular problem.

For nonlinear static analysis, the loads are applied in incremental steps through the use of "time" curves. A time curve prescribes how a load or a restraint changes during the solution steps. For nonlinear dynamic analysis, and nonlinear static analysis with time-dependent material properties (e.g., creep), "time" represents the real time associated with the loads application.

The choice of "time" step size depends on several factors such as the level of nonlinearities of the problems and the solution procedure. A computer program should be equipped with an adaptive automatic stepping algorithm to facilitate the analysis and to reduce the solution cost [2].

In nonlinear static analysis, the basic set of equations to be solved at any "time" step, t+Dt, is:

$$ {}^{t+Dt}\{R\} - {}^{t+Dt}\{F\} = 0, $$

where:

${}^{t+Dt}\{R\}$ = Vector of externally applied nodal loads

${}^{t+Dt}\{F\}$ = Vector of internally generated nodal forces.

Since the internal nodal forces ${}^{t+Dt}\{F\}$ depend on nodal displacements at time t+Dt, ${}^{t+Dt}\{U\}$, an iterative method must be used. The following equations represent the basic outline of an iterative scheme to solve the equilibrium equations at a certain time step, t+Dt,

$$\{DR\}^{(i-1)} = {}^{t+Dt}\{R\} - {}^{t+Dt}\{F\}^{(i-1)}$$

$${}^{t+Dt}[K]^{(i)}\,\{DU\}^{(i)} = \{DR\}^{(i-1)}$$

$${}^{t+Dt}\{U\}^{(i)} = {}^{t+Dt}\{U\}^{(i-1)} + \{DU\}^{(i)}$$

$${}^{t+Dt}\{U\}^{(0)} = {}^{t}\{U\};\quad {}^{t+Dt}\{F\}^{(0)} = {}^{t}\{F\}$$

where:

${}^{t+Dt}\{R\}$ = Vector of externally applied nodal loads

${}^{t+Dt}\{F\}^{(i-1)}$ = Vector of internally generated nodal forces at iteration (i)

$\{DR\}^{(i-1)}$ = The out-of-balance load vector at iteration (i)

$\{DU\}^{(i)}$ = Vector of incremental nodal displacements at iteration (i)

${}^{t+Dt}\{U\}^{(i)}$ = Vector of total displacements at iteration (i)

${}^{t+Dt}[K]^{(i)}$ = The Jacobian (tangent stiffness) matrix at iteration (i).

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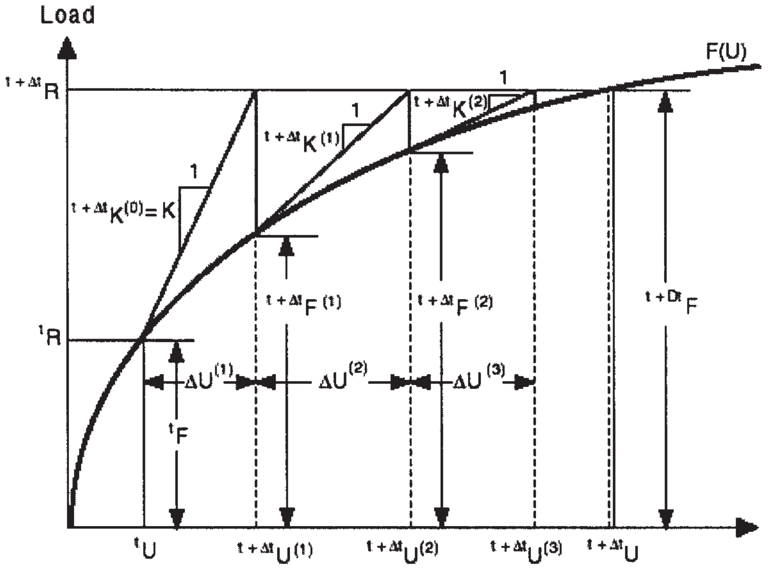

Fig. 1. Newton-Raphson Scheme

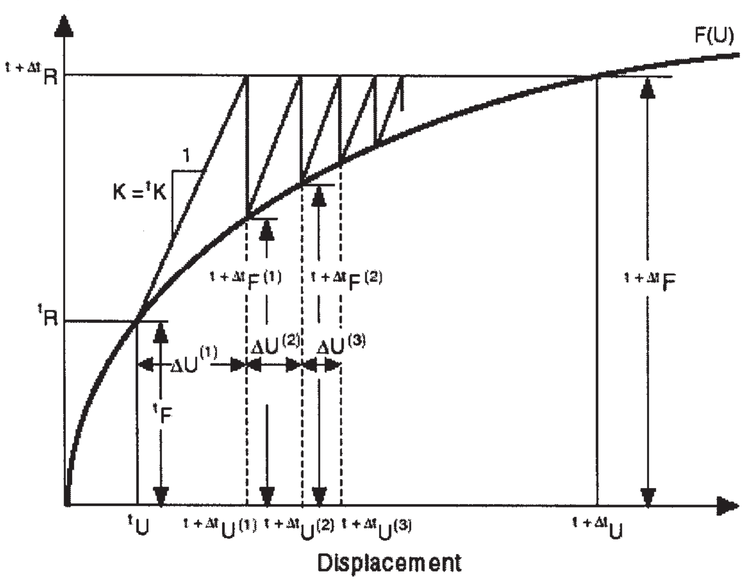

Fig. 2. Modified Newton-Raphson Scheme

There are different schemes to perform the above iterations. Brief descriptions of two methods of the Newton type are presented below:

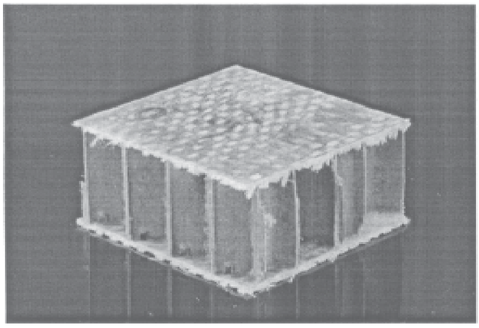

Fig. 3. Real life specimen

Newton-Raphson Scheme

In this scheme (fig. 1), the tangential stiffness matrix is formed and decomposed at each iteration within a particular step as shown in the figure below. The NR method has a high convergence rate and its rate of convergence is quadratic. However, since the tangential stiffness is formed and decomposed at each iteration, which can be prohibitively expensive for large models, it may be advantageous to use another iterative method.

Modified Newton-Raphson Scheme

In the following scheme (fig. 2), the tangential stiffness matrix is formed and decomposed at the beginning of each step (or as specified when defining the properties of the study) and used throughout the iterations as shown in the figure below [3].

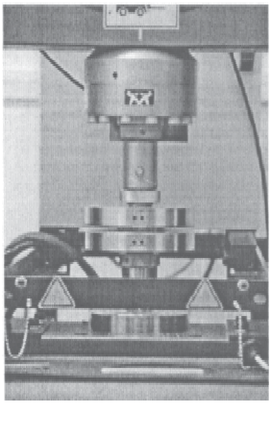

Fig. 4. Compression test

Material model

For the purpose of this paper a proper specimen for testing is needed. The geometrical model and materials are the same as the specimen depicted below (fig. 3).The strain-stress curve of the material was determined by a compression test as is plotted in figure 4 [5, 8]. Using this type of testing the properties of the resin and the resin

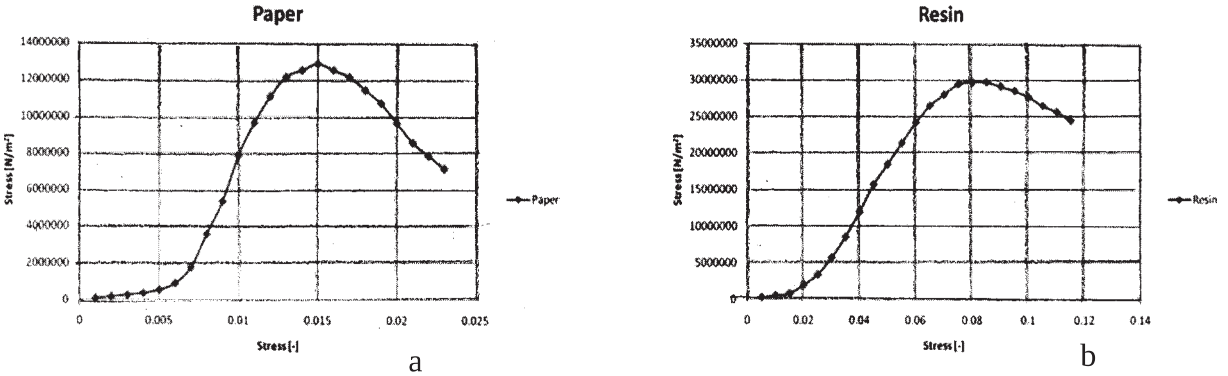

Fig 5. Strain-Stress charts

Table 1
MECHANICAL PROPERTIES OF MATERIALS USED

Material	Poisson's Ration [-]	Density [kg/m^3]
Paper	0.35	600
Resin	0.45	2240

impregnated paper were determined. These data are presented in figure 5. The chart on the left (a) presents the strain-stress curve for the paper and the chart on the right (b) the strain-stress curve for the resin.

The other mechanical properties required for a complete analysis of the honeycomb sandwich were taken from Solid Works material library and are presented in table 1.

Figure 6 plots the dimensions of the sandwich analyzed, layout of the materials and the areas where the loads were applied. The 40 mm diameter circle determines the area outside of which the boundary conditions were placed. As it can be seen, in the figure depicted below, the caps of the sandwich are made of epoxy resin and the honeycomb core is made of resin impregnated paper. All of the dimensions are in millimeters. The double side walls correspond to the real life model presented above and are a consequence of the manufacturing procedure [6].

Calculus model

At first, a virtual geometrical model was created using the dimensions presented in the picture above. For means of saving computing power and time, only half of the structure was created. The virtual model is plotted in Figure 7.

The meshing procedure used a tetrahedron element with a size of 2 mm and a tolerance of 0.1 mm. There

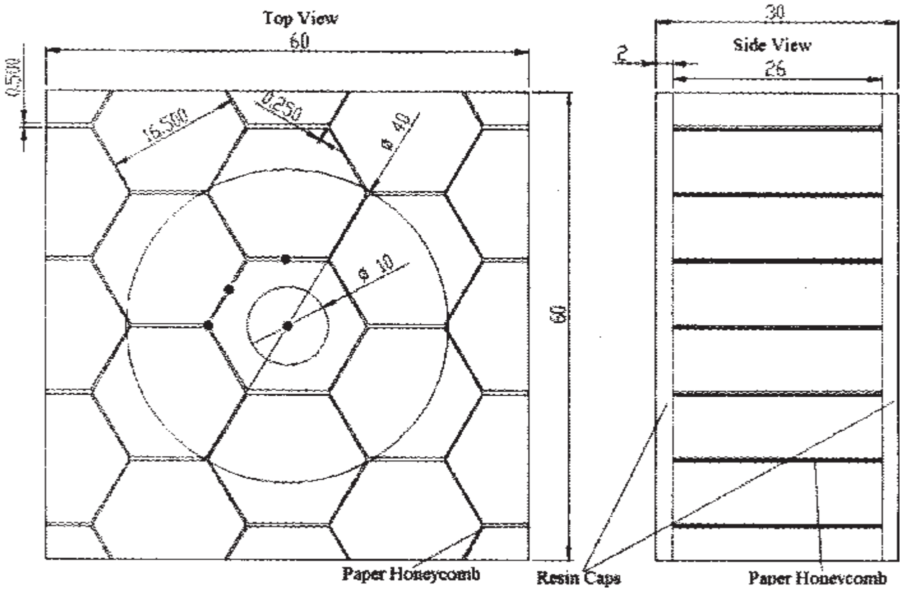

Fig. 6. Specimen dimensions, materials layout, load application area

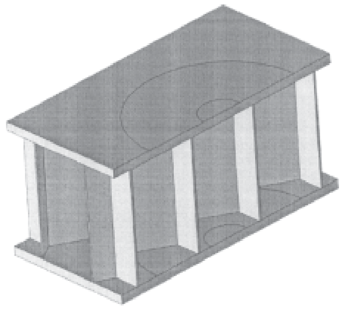

Fig. 7. Geometrical model

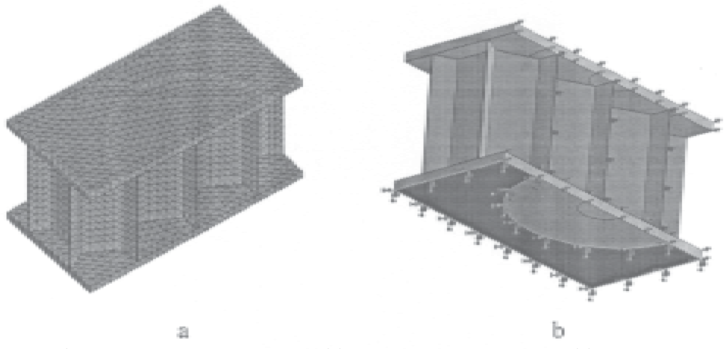

Fig. 8: Mesh, boundary conditions and symmetry conditions

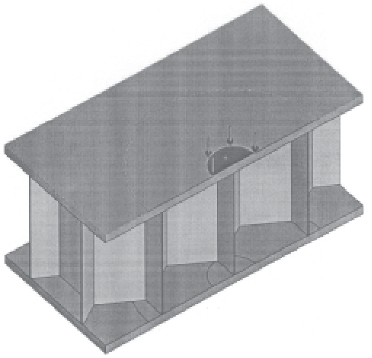

Fig. 9: Load area

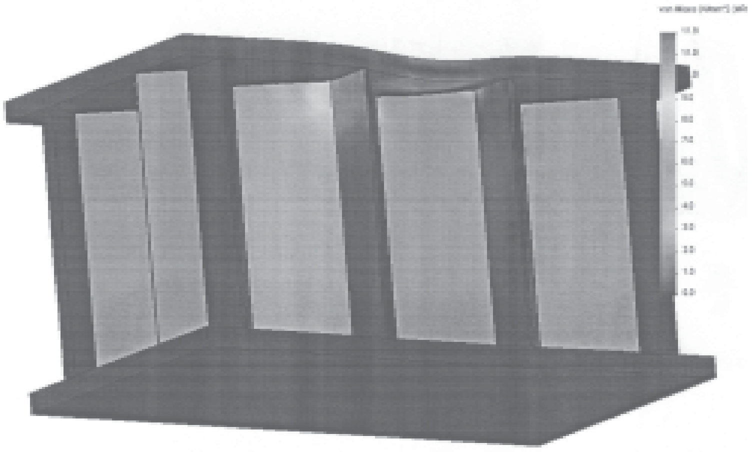

Fig. 10. Stress chart, cell center applied load

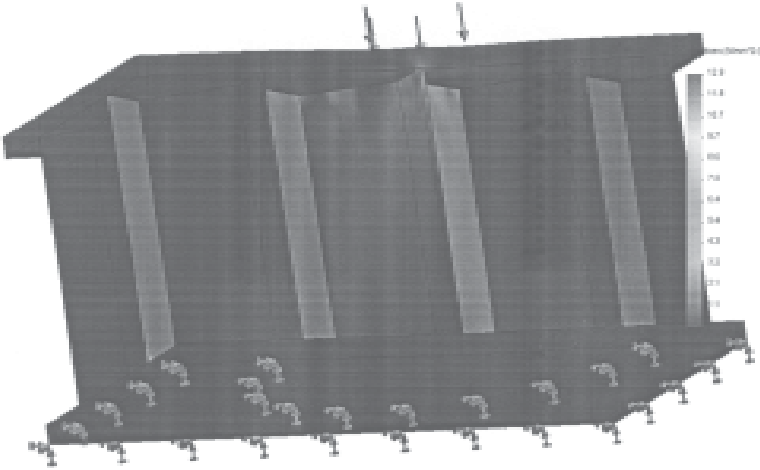

Fig. 11. Stress chart, thick wall applied load

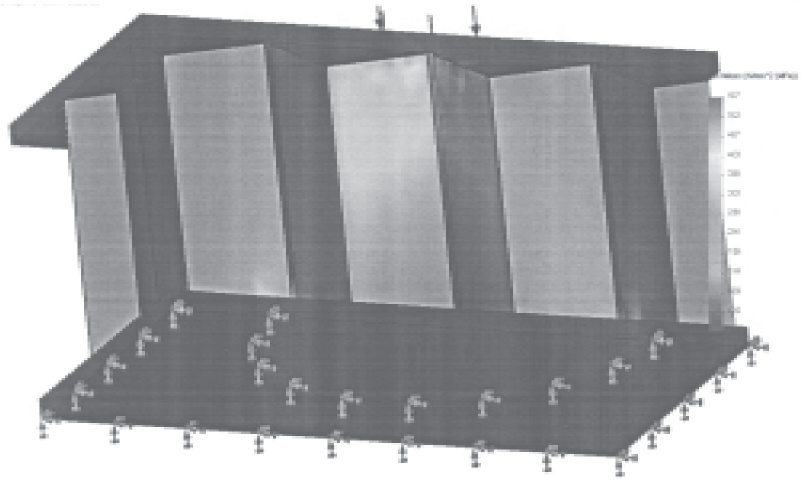

Fig. 12. Stress chart, three wall junction applied load

were obtained a total number of 37213 nodes and 19840 elements. The mesh is presented in figure 8a.

The boundary conditions and symmetry conditions are plotted in figure 8b. An area outside a 20 mm radius circle from the center of the specimen was used for creating and applying the boundary conditions represented by three way darts. At the side of the specimen the symmetry conditions are shown by one way darts.

A 10 N load was applied on a 10 mm diameter circle as it is show in figure 9. Four areas of appliance were defined and presented in figure 6 as red dots, representing the center of the circle mentioned above. The areas of interest were at the center of one cell, at a junction of three honeycomb walls, at the middle of a thick wall and at a middle of a thin wall. The figure below presents only one case of these loads.

The model was created using Solid Works software and the analyses were created using the nonlinear solver module called Simulation. Due to the nonlinear nature of the materials used, as is presented in figure 5, the iterative Newton – Raphson method was applied in this case. All of the analyses converged after 13 iteration steps.

Comparative analyses

The results of the analyses are plotted as stress distribution charts in figures 10-13.

First chart (fig. 10) presents the stress distribution in the case of a load applied at the center of one cell. The stress distribution underneath the load area is uniform but some local problems appear at the junction of the nearest wall

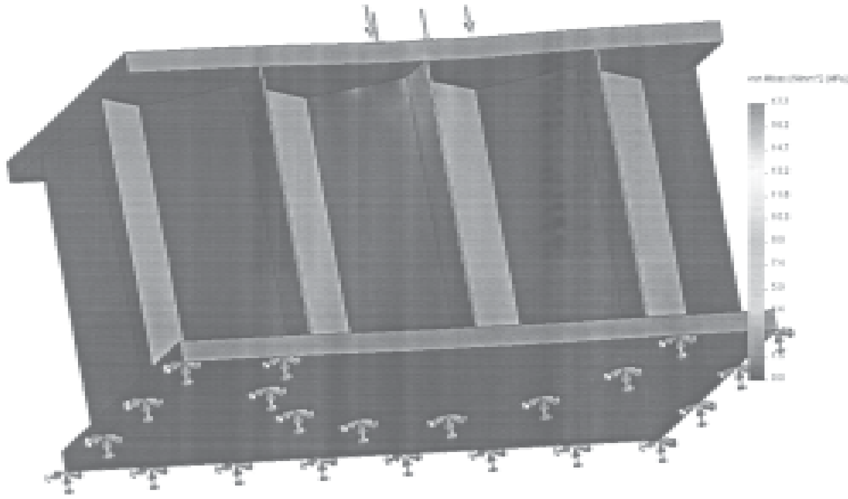

Fig. 13: Stress chart, thin wall applied load

from the center of the cell and the resin cap. The maximum von Mises equivalent stress is at a value of 11.9 MPa, almost 50% higher than in the area of load application. All of the other areas register only small amount of stress, values averaging at about 2 MPa.

Second chart (fig. 11) depicts the stress distribution for the load applied at the middle of a thick wall. Maximum value of 12.9 is registered in the honeycomb wall, exactly at the center of the load distribution circle. Von Mises equivalent stress distributions in the walls next to the thick wall is irregular but the maximum value is at about 5.4 MPa.

Third chart (fig. 12) shows the stress distribution in the case of the load applied at a junction of three walls (two thin and one thick). The maximum stress has a value of 5.7 MPa and is registered at the top of the thin walls. Also another large value (3.8 MPa) of stress is registered at the bottom of the walls of the nearest cells.

The last chart (fig. 13) plots the stress distribution for the load applied at the middle of a thick wall. This case presents the biggest values of von Mises equivalent stress at a value of 17.7 MPa, exactly at the center of the load distribution circle. The near walls show only small amounts of stress (10.3 MPa) in relation with the maximum value, but almost twice the amount than in the other cases.

For a better understanding of stress distribution and importance of load appliance points two similar areas of interest were probed by nodal sensors for each of the load cases. First area was defined at the edge of the load circle and the second along the height of the nearest wall from the load application point. The results from these probes are depicted in the following two charts.

Figure 14 represents the stress values at nodes for the first area. These results are for the resin cap of the sandwich. It can be seen that the maximum local stress is obtained for the cell centered load, with a value of 2.5 MPa. The other three cases are similar, but with a small increase in value and a slight different shape of the curve for the junction. The thin and thick walls are almost the same in terms of values and shape.

Figure 15 plots the stress values for the second area. The peak in the thin wall is most obvious in this chart with the maximum value at about 18 MPa. The cases of centered and thick wall show a small peak between nodes 1 to 4 with higher values for the junction. From node 5 up to node 22 the decrease of stress is linear. The thick case presents a linear decrease from a value of 4.3 MPa along all nodes.

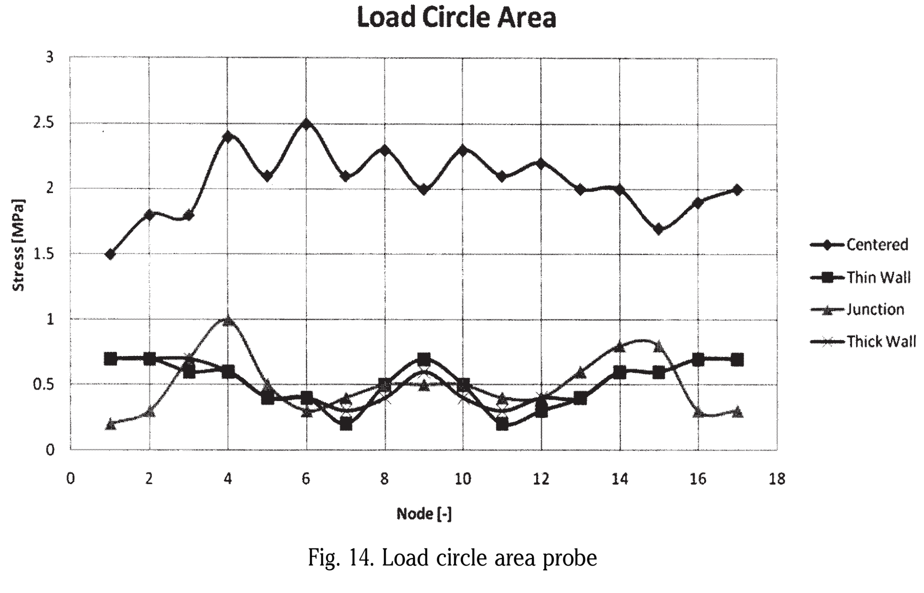

Fig. 14. Load circle area probe

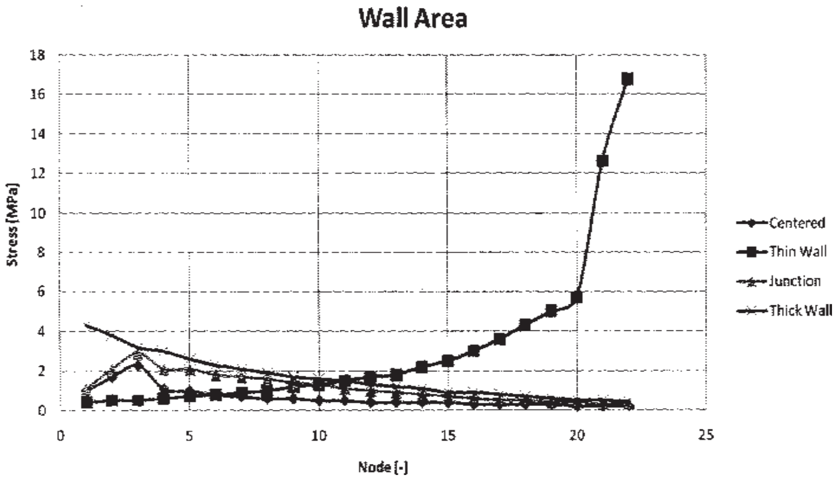

Fig. 15. Wall area probe

Conclusions

All the results obtained from the nonlinear analyses previously presented can lead us to determine the influence of load positioning upon a honeycomb core sandwich. The need for nonlinear analyses is justified by the strain-stress curves of the materials previously presented.

The honeycomb core sandwich structure made of resin and resin impregnated paper, requires a much rigorous approach during numerical calculus. The innovative part of this paper consists of a different approach for the load and boundary conditions placements, an in depth analyses of the core material and the stress distribution that appears underneath the loading area of the caps and into the honeycomb walls.

Using these results we can determine which area is best suited for impact absorption and which for sustaining high loads.

If we are interested in obtaining a structure that can dissipate kinetic energy from an impact and act as a damper the best place for placing a load at the middle of the "thin wall". This will lead to a collapse in the honeycomb structure, but much of the energy from an impact will absorb [7].

The other possibility is that we need the structure to sustain as much load as possible, dynamic or static. The best possible case for this is to place the load at the three wall "junction". This way the maximum stress in the sandwich will have a value of 5.7 MPa and will spread along the honeycomb walls.

The case of "thick wall" is oriented towards the first option, but with higher loads capabilities and the case of "centered" load is suited for high loads with small dampening factor.

These results can be used to create new materials or structure models with great use in impact protection, placing mounting brackets on honeycomb core sandwich for sustaining other structures and many other areas of engineering and industry.

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