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Finite Element Analysis of Loading Area Effect on Sandwich Panel Behaviour Beyond the Yield Limit

Salih Akour and Hussein Maaitah

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1. Introduction

Research efforts continuously are looking for new, better and efficient construction materials. The main goal of these researches is to improve the structural efficiency, performance and durability. New materials typically bring new challenges to designer who utilizes these new materials. In the past decades various sandwich panels have been implemented in aerospace, marine, architectural and transportation industry. Light-weight, excellent corrosion characteristics and rapid installation capabilities created tremendous opportunities for these sandwich panels in industry. Sandwich panel normally consists of a low-density core material sandwiched between two high modulus face skins to produce a lightweight panel with exceptional stiffness as shown in Figure 1. Face skins act like flanges of an I-beam. These faces are typically bonded to a core to achieve the composite action and to transfer the forces between sandwich panel components.

1.1. Main principles of sandwich structures

Typical sandwich composite construction consists of three main components as illustrated in Figure 1. The sandwich consists of two thin, stiff and strong faces are separated by thick, light and weaker core. Faces and core materials are bonded together with an adhesive to facilitate the load transfer mechanism between the components, therefore effectively utilize all the materials used. The two faces are placed at a distance from each other to increase the moment of inertia, and consequently the flexural rigidity, about the neutral axis of the structure.

In sandwich structure, typically the core material is not rigid compared to face sheets; therefore, the shear deflection within the core is insignificant in most cases. The shear deflection in the faces can be also neglected. The effect of shear rigidity in the core is shown

in Figure 2. Figure 2a shows an ideal sandwich beam using relatively stiff core, therefore the two faces cooperate without sliding relative to each other. Figure 2b shows a sandwich beam using weak core, therefore the faces are no longer coupled together effectively and each face works independently as plates in bending. The use of weak core in shear results in significant loss of the efficiency of the sandwich structures. In a typical sandwich panel the faces carry the tensile and compressive stresses. The local flexural rigidity of each face is typically small and can be ignored. Materials such as steel, stainless steel, aluminum and fiber reinforced polymer materials are often used as materials for the face. The core has several important functions. It has to be stiff enough to maintain the distance between the two faces constant. It should be also rigid to resist the shear forces and to prevent sliding the faces relative to each other. Rigidity of the core forces the two faces to cooperate with each other in composite action. If these conditions are not fulfilled, the faces behave as two independent beams or panels, and the sandwich effect will be totally lost. Furthermore, rigidity of the core should be sufficient to maintain the faces nearly flat, therefore prevent possibility of buckling of the faces under the influence of compressive stress in their plane. The adhesive between the faces and the core must be able to transfer the shear forces between the face and the core.
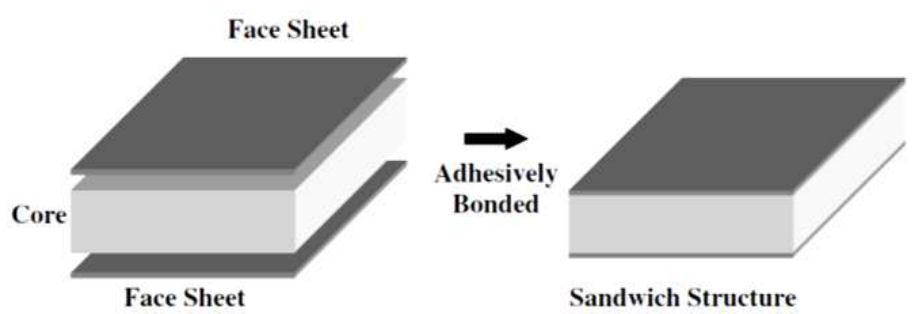
**Figure 1.** Schematic of sandwich construction

1.2. Applications

Sandwich construction provides efficient utilization of the materials used for each component to its ultimate limit (Zenkert, 1997). The sandwich structure offers also a very high stiffness-to-weight ratio. It enhances structure flexural rigidity without adding substantial weight and makes it more advantageous as compared to composite materials. Sandwich constructions have superior fatigue strength and exhibit superior acoustical and thermal insulation. Sandwich composites could be used in a wide variety of applications such as:

Aerospace Industry: Sandwich composites are increasingly being used in the aerospace industry because of their bending stiffness-to-weight ratio. Floorboards, composite wing, horizontal stabilizer, composite rudder, landing gear door, speed brake, flap segments, aircraft interior and wingspans are typically made of sandwich composites.

Marine Industry: Sandwich composites are ideally suited for the marine industries most advanced designs. The foam cores meet the critical requirements of strength, buoyancy and

low water absorption. Applications include the construction of bulkheads, hulls, decks, transoms and furniture.
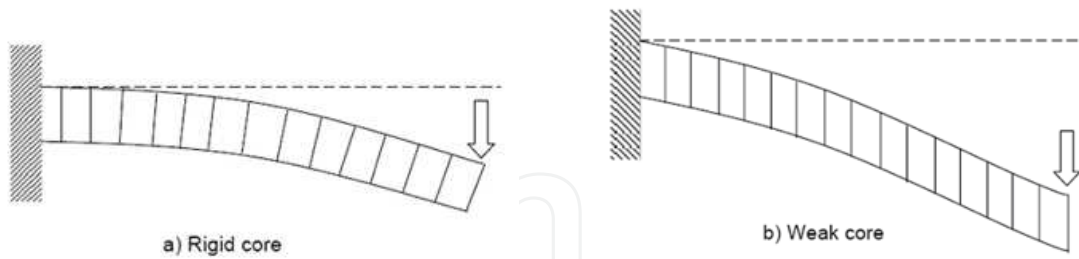
Figure 2. Presentation of the effect of a) rigid and b) week core.

Transportation Industry: High strength-to-weight ratios of sandwich composites offer great advantages to the transportation industry. The insulating, sound damping properties and low cost properties make them the choice materials for the constructions of walls, floors, doors, panels and roofs for vans, trucks, trailers and trains.

Architectural Industry: The foam offers an excellent thermal and acoustical insulation which makes it ideal choice for the architectural industry. Typical applications include structural columns, portable buildings, office partitions, countertops and building facades.

1.3. Literature review

Work on the theoretical description of sandwich structure behaviour began after World War Two. (Plantema, 1966) published the first book about sandwich structures, followed by books by (Allen, 1969), and more recently by (Zenkert, 1995). Although (Triantafillou and Gibson, 1987) developed a method to design for minimum weight, and reported the failure mode map of sandwich construction, without considering the post yield state of the sandwich structure.

The basic sandwich structure theory presented in all these texts is generally called the classical sandwich theory. This theory assumes that:

- The core carries the entire shear load in sandwich beams and plates.
- The face sheets carry the entire bending load.
- Core compression is negligible.
- This theory states that the above–mentioned assumptions are true if:
  1. The core and face sheets are elastic.
  2. The overall length to thickness ratio is high.
  3. The face sheet thickness is small compared to the overall thickness.
  4. The ratio of mechanical properties between the face sheet and the core is high.

With these assumptions, a sandwich structure is considered to be incapable of acquiring additional load carrying capacity once the core yields.

(Mercado and Sikarskie, 2000) reported that the load carried by sandwich structures continue to increase after core yielding. Knowing that the core could not carry additional load after yield, this increasing load carrying capacity of post yield sandwich structure

initiates the postulation that the additional shear load was transferred to the face sheets. To account for the above-mentioned phenomenon, (Mercado et al, 1999) developed a higher order theory by including a bilinear core material module. This theory yields a fairly accurate prediction on the deflection of a foam cored sandwich structure in four point bending (Mercado et al, 2000). In addition, this theory does not take into account the core compression under localized load, or any geometric non-linearity. The classical sandwich beam theory also assumes that in-plane displacements of the core through its depth are linear. In other words, it was assumed that the core thickness remains constant and cross-sections perpendicular to the neutral axis remain plane after deformation. This assumption is generally true for traditional core material such as metallic honeycomb. However, this assumption is not suitable for soft, foam-based cores, especially when the sandwich structure is subjected to a concentrated load (Thomsen, 1995). With a much lower rigidity compared to metallic honeycomb, foam-based cored sandwich structures are susceptible to localized failure. Insufficient support to the face sheets due to core compression near the application points of concentrated loads can lead to failures such as face sheet/ core delamination, face sheet buckling, and face sheet yielding. This localized non-linearity is reported by many researchers such as (Thomsen, 1995), (Thomsen, 1993), (Rothschild 1994), (Caprino, 2000), and (Gdoutos et al, 2001). The shear distribution at localized failure points has not been well defined. (Miers, 2001) investigated the effect of localized strengthening inserts on the overall stiffness of a sandwich structure. This localized strengthening increases the rigidity of the sandwich structure, but the addition of high stiffness inserts complicates the manufacturing process of sandwich structure.

To design an efficient sandwich structure, it is vital to understand the behavior of each layer in the structure. Classical sandwich theory (Zenkert 1995, Plantema 1966, Allen 1969), higher order theory by Mercado (2000) and high order theory developed by Frostig et al. (1992) could predict the sandwich panel behavior fairly accurate in the linear range. However, these theories could not give an accurate prediction of the sandwich structure behavior after core yielding. Large deflection of sandwich structures due to core yielding could vary the direction of the applied load on the structure.

1.4. Research objective

To design an efficient sandwich structure, it is vital to understand the load distribution pattern in each layer of the structure. Most of the previous efforts are made by using classical sandwich theory, and higher order theory, where high order theory predicted the sandwich panel behavior fairly well in the linear range. However, these theories could not give an accurate prediction of the shear distribution in each layer after core yielding. Large deflection of sandwich structures due to core yielding could vary the direction of the applied load on the structure. Change in loading direction would obviously change the shear distribution in the sandwich structure. In order to investigate the exact change of shear distribution due to distributed loads, as well as geometric nonlinearity and localized core failure, finite element analysis is used in this research effort. The main objective of this research is to investigate the following:

1. Post yield behavior of sandwich panel.
2. Effect of geometric non-linearity under distributed loads.
3. The effect the size of the distributed load area on the behavior of the sandwich panel beyond the core yield limit for different types of materials is investigated. These parameters are the determining factors of the significance of geometric non-linearity and core material nonlinearity

The above investigation is done in view of the following points:

1. Localized core yielding occurs mainly through core compression. Therefore, analysis should be done using material properties determined from compression test.
2. For practical purposes, the assumptions that have been made in developing the sandwich panel theory eliminated part of the problem physics.
3. The Finite Element Model (FEM) is extended to include the relative dominance of core shear failure and face sheet yielding.
4. Localized loads are modeled as load on small partitioned area to better simulate the actual loading condition.
5. Experimental verification is conducted for selected cases.

2. Physical model

This section presents the physical model of the sandwich panel, which includes geometry, boundary conditions as well as the materials used in the investigation.

2.1. Sandwich panel geometry

The sandwich panel consists of two face sheets made of metal. The thickness of each face is **t**. Soft core of **c** thickness is sandwiched between those face sheets. The core material is made of foam which is soft compared to the face sheets .The panel is square in shape. The side length is designated by **a.** Figure 3 illustrates the sandwich panel geometry whereas the dimensions of the sandwich panel are shown in Table 1.
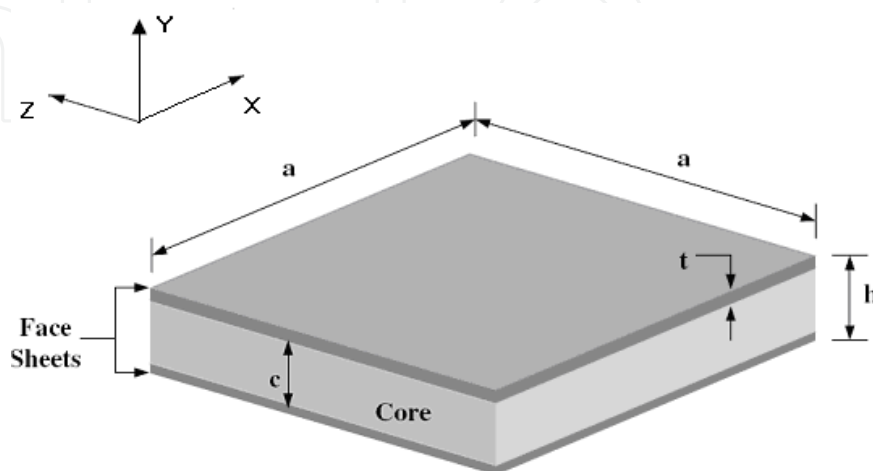
Figure 3. Illustration sandwich plate geometry.

Parameter	Dimension	Note
a	600 mm	Constant
t	1.0 mm	Constant
c	30 mm	Constant

Table 1. The value of the parameters shown in Figure 3.

2.2. Assumptions

This research takes into consideration the geometric non-linearity as well as the material nonlinearity. The following assumptions are made to simplify the model without losing the problem physics:

1. Face sheets and core are perfectly bonded.
   The FEM model assumes no delamination occur between layers.
2. Face sheets remain elastic at all time.
   Due to the significantly higher yield strength and modulus of elasticity of the face sheets compared to the core, face sheets are assumed to remain elastic throughout the loading for simply supported panel. The analysis stops when the face sheets start to yield.
3. Geometric non-linearity has a significant effect:
   Geometric non-linearity is considered to have significant effect on the load distribution on each layer of the sandwich structure.

2.3. Boundary condition

Due to the symmetry of the sandwich panel (symmetric over X-axis and symmetric over Z-axis), only quarter of it is being modeled. Such symmetric boundary conditions are applied of the X-axis and Z-axis. The two planes of symmetry of the panel have symmetric boundary conditions, (see Fig. 4). A simply supported boundary condition is applied to strip area of the quarter panel as shown in Fig. 5. This simulates the simply supported condition of the panel. The loading area is square in shape, its side length varies in steps of 100, 200, 400 and 600mm for full panel dimension. But when dealing with quarter panel, the side length is 50, 100, 200, and 300mm

2.4. Study parameters

The main parameters that have influence on the performance of the sandwich plate are, the loading area on which the load is distributed and the core material stiffness.

2.4.1. Loading

The load is applied to the sandwich top face sheet as a distributed load which is increased gradually (step by step) till the face sheet stress reaches yield stress or the core material

reaches fracture limit. The distributed load is applied on the top surface of the sandwich panel. The area on which the distributed load is applied (see Figure 5 and 7) is located at the middle of the top face sheet plate. The loading area at the middle top face of sandwich panel is square in shape. This area has been varied from 100X100 mm² through 200X200 mm², 400X400 mm², and 600X600 mm² so the ratio of these areas relative to the total area of the sandwich panel is 1/36, 4/36, 16/36 and 36/36 respectively.
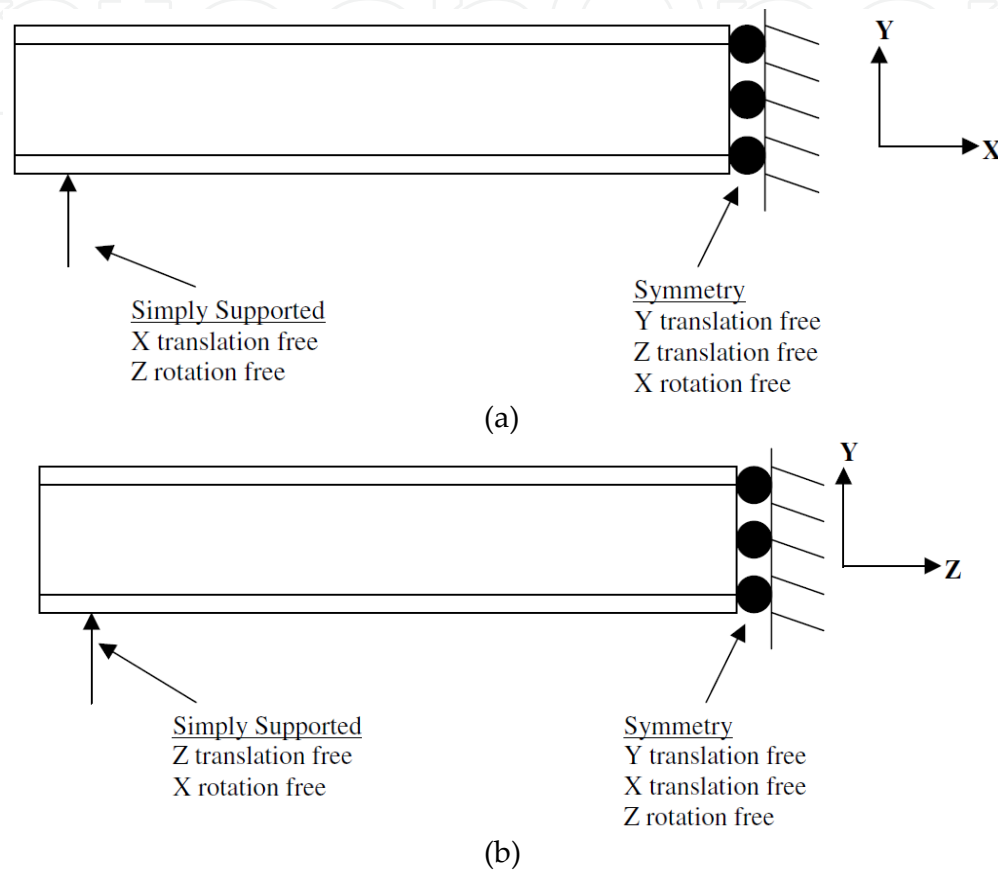
Figure 4. Sandwich panel boundary condition for a) X-Y plane and b) Y-Z plane.

2.4.2. Core material

In the current research, different materials are used. Their modulus of elasticity is varying from 37.5 MPa through 138.6 MPa, 180 MPa, and 402.6 MPa as shown in Table 2. Core thickness is selected to be 30mm as shown in Table 1.

2.5. Material properties

The core of sandwich structure is used to separate the two faces, most often identical in material and thickness, which primarily resist the in plane and bending load. The core is mainly subjected to shear so that the core shear strain produces global deformations and core shear stresses. Thus, core must be chosen such that not to fail under applied transverse load. It should have shear modulus that is high enough to give the required stiffness.

Furthermore, its young's modulus normal to the faces should be high enough to prevent contraction of the core thickness and therefore a rapid decrease in flexural rigidity. The core should have low density in order to add as little as possible to the total weight of sandwich structure. Because of low density requirement, core materials are very different from face sheet materials. A detailed characterization of their mechanical behavior is essential for their efficient use in structural application. Four types of foam H100, H250, AirexR63.50 and Herex C70.200 are investigated.
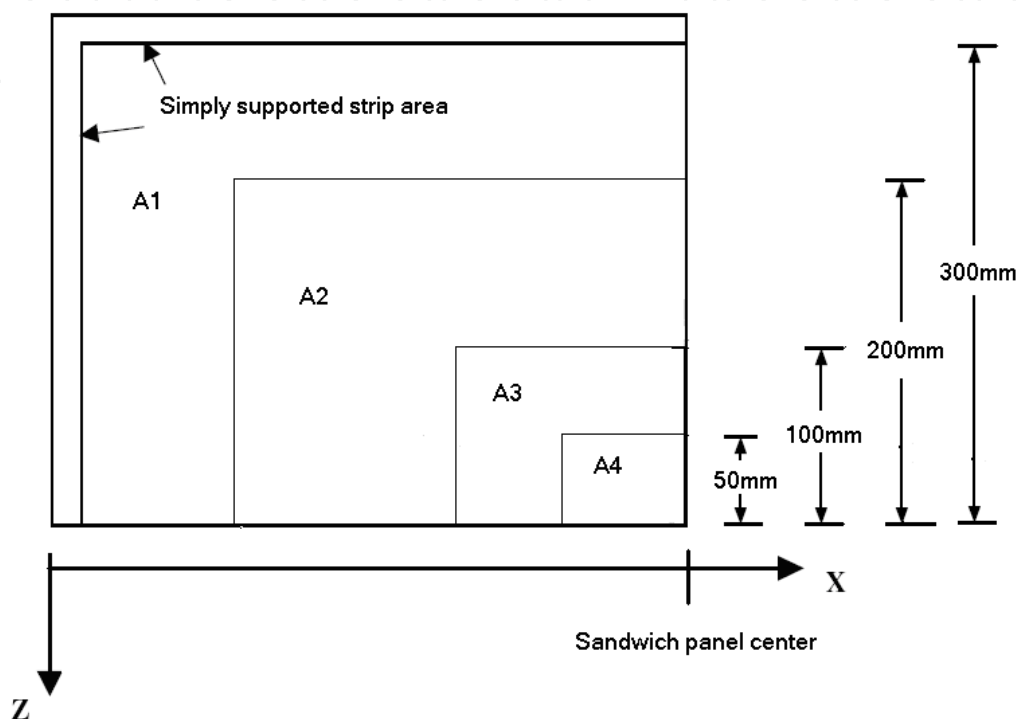
Figure 5. Panel span overview of quarter sandwich panel for different loading area

2.5.1. Mechanical properties for face sheet

Material properties for the sandwich plate face sheets are taken from (Boyer and Gall (Eds.), 1991). Aluminum 3003-H14 is a type of aluminum alloy that has high resistance to corrosion and is easy to weld is used in this investigation. The 3003-aluminum family is normally used in the production of cooking utensils, chemical equipment, and pressure vessels. The face sheets are assumed to remain elastic at all times. Therefore only elastic material properties are required for the face sheets and they are presented in Table 2.

2.5.2. Mechanical properties for core

This subsection presents the core material properties used to model the sandwich panel. In all cases, face sheets of the sandwich structures are assumed to remain elastic throughout the analyses. Therefore, only core materials require a good post yield behavior descriptions. The core materials undergo plastic deformation; hence there is a need to obtain a full description of the core materials' behavior upon yield initiation.

Airex R63.50 has high fatigue strength, high three-dimensional formability, and high resistance to dynamic loads. Materials in Airex R63 family are widely used in the production of marine hulls and lightweight cars due to the appreciation of their low density and high strength and stiffness to weight ratio. Airex R63.50 is presented in Table 2.

Material properties of the HerexC70.200 foam core is obtained from (Rao, 2002) work. Herex C70.200 is an isotropic and stiff foam material with high stiffness and strength to weight ratios. The materials in Herex C70 family have excellent chemical resistance and low thermal conductivity and water absorption. The appreciation of these inherent properties of Herex C70 materials makes this material a popular choice for the core materials of structural sandwich structures in marine and railway applications. The stress strain curve of this material is presented in Figure 6.

In this research a first-order idealized core material property module suggested by (Mercado, Sikarskie, 1999) is used. This first-order idealized model, also called the bi-linear model, describes the material properties of the core with the stress strain curve as shown on Figure 6a and 6c.

The other material used in this research is linked PVC close called cellular foam (divinycell). The type of divinycell, H100, H250 with densities of 100 and 250 kg/m^3, their mechanical properties are stated in Table 2 and their stress strain curves are shown in Figure 6b and 6d respectively.

Material	Property source	Young's modulus (MPa)	Poisson's ratio	Shear modulus (Mpa)	Shear strength (Mpa)	0.2% offset yield strength (Mpa)	Strain at yield popup (mm/mm)
Face sheet : Aluminum 3003-H14	Boyer and Gall 1991	69,000	0.33	25,000	120	145	Not available
Core A : AirexR63.50	Rao, 2002	37.5	0.335	14.05	0.45	0.637	0.019
Core B: H100	Kuang, 2001	138.6	0.35	47.574	1.2	1.5	0.0108225
Core C: Herex C70.200	Rao, 2002	180	0.37	65.69	1.6	2.554	0.0162
Core D: H250	Kuang, 2001	402.6	0.35	117.2	4.5	5	0.014

Table 2. Compression of sandwich panel material properties

3. Finite element model

This section presents the development of finite element models for simply supported sandwich panel. Detailed descriptions of the boundary conditions, element types, and the

loading are presented in the coming subsections. The finite element software used in the development of the finite models is (I-DEAS Master Series 10 1999). The relatively robust and user-friendly solid modeling and finite element meshing interface are the main advantages of this solid modeling and finite element software.

(a) (b)

(c) (d)
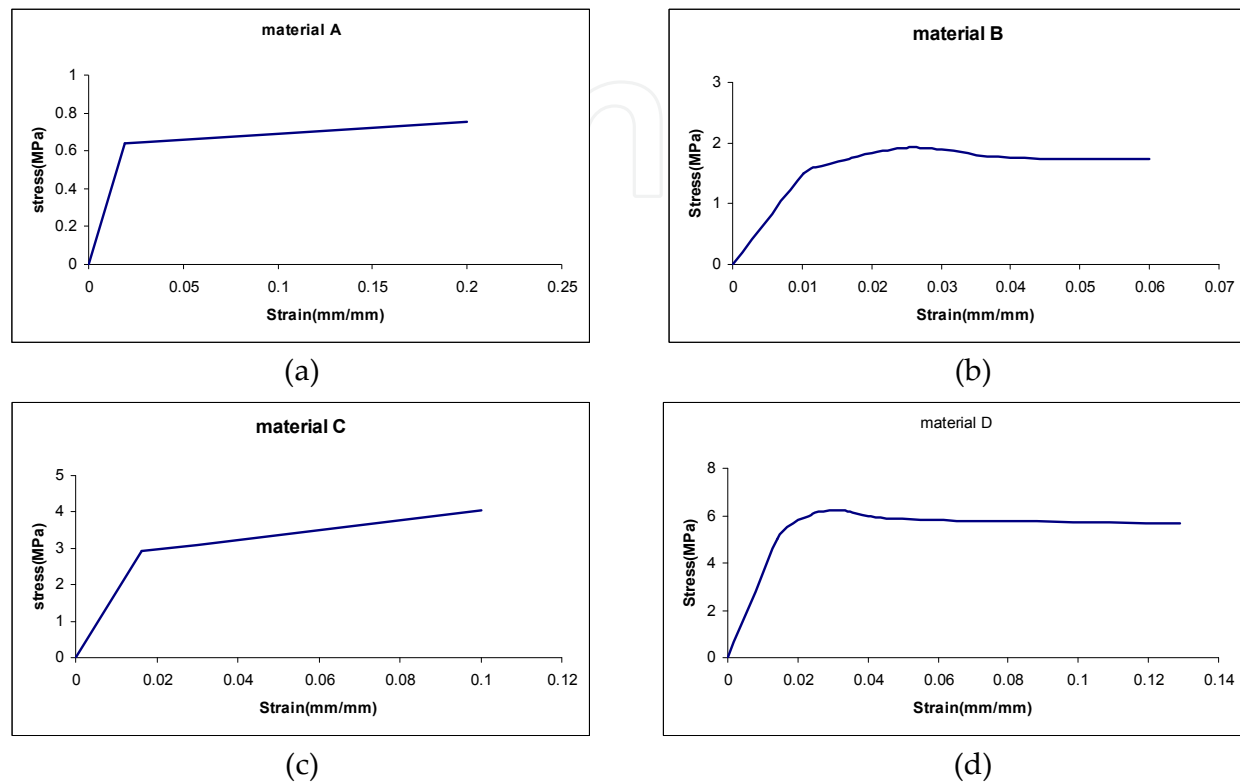
Figure 6. Stress strain curve for a)material A: AirexR63.50 (Rao, 2002), b) material B: H100 (Kuang, 2001), c)material C: Herex C70.200 (Rao, 2002), d) material D: H250 (Kuang, 2001)

3.1. Model assumptions

All the finite element model analyses done in this research involves the use of non-linear analysis capability of I-DEAS, which includes geometric non-linearity and material nonlinearity. With geometric non-linearity, the software takes the effect of geometry changes into account while calculating the solution. Using material non-linearity option the non-linear behavior of the material response (i.e. post yield material properties) is taken into account.

Below are the assumptions made for the Finite Element Model:

1. Face sheets and core are perfectly bonded:
   The numerical model assumes no delamination occur between layers. This assumption is applied by utilizing the partitioning option in the preprocessing module of the software. This option allows the analyst to deal with the whole volume of the structure as one unit also it allows the analyst to assign different material for each partitioned volume.

2. Face sheets remain elastic all the time:

   Due to the high yield strength and high modulus of elasticity of the sandwich face sheets compared to the core, face sheets are assumed to remain elastic throughout the loading for the simply supported panel.

3. Load scenarios are quasi-static:

   The loading cases considered are modeled quasi-static instead of dynamic. Incremental loadings are applied slowly during the actual experiments (i.e. simulates exactly the real situation). Therefore, the type of analysis done for this research effort is "static, non-linear analysis".

4. Geometric non-linearity has a significant effect:

   Geometric non-linearity is considered to have significant effect on the load distribution on each layer of the sandwich structure. Therefore, all finite element analysis that is done takes into consideration the geometric non-linearity. This is the main difference between the numerical models and the theoretical models. Classical sandwich plate theory and higher order theory do not take shape change of the sandwich structures into account.

5. The panel is simply supported from all sides. It is partitioned into three layers, forming three bonded material layers.

3.2. Finite element mesh and boundary conditions

The symmetric nature of the problem allows only quarter of the whole panel to be meshed. The boundary conditions applied are shown on Figures 4 and 5. The two planes of symmetry of the panel have symmetric boundary conditions, where in-plane displacements and rotation about an axis respective normal to the symmetry plane is allowed. A simply supported boundary condition is applied to the two other sides of the quarter panel. A distributed load is applied on the top surface of the sandwich panel. The area in which the distributed load is applied is varying as shown in Figures 5 and 7.

(a)   (b)
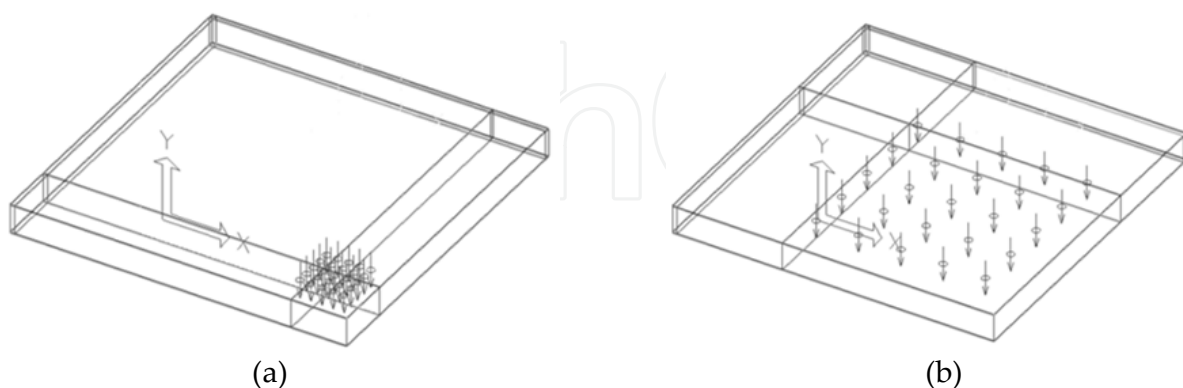
Figure 7. The loading area with side length a) 50 mm and b) 200 mm.

The panel is loaded with a set of loads that are varying slowly with time, and the analysis is carried out at each load step. The finite element software is set in such a way to solve the model at each load step. This allows all the analysis to be done in a single run of the finite

element model. As a result of this, the model would consume less memory space because one single solid model and finite element model can be used for all load steps.

The numerical model utilizes the map meshing facility in I-DEAS. By controlling the number of nodes along each edge of the solid model, this function provides full control of the mesh size. The element size is chosen by referring to (Miers, 2001) work in mesh refinement. (Mires, 2001) recommended a core element size of 1.5 mm and face element size of 3 mm in order to achieve convergence in the data obtained. For the current case constant mesh density is ensured with the mapped meshing function. This is important because constant mesh density ensures that the data collected from any region in the panel are of the same degree of resolution. Three-dimensional solid brick elements (20 node brick element) are used in this analysis. Second order (parabolic) brick elements are chosen over the first order (linear) brick elements in order to better interpolate the data between nodes. Figure 8 shows the FEM mesh model of the sandwich panel and the brick element utilized in FEM.

(a)   (b)
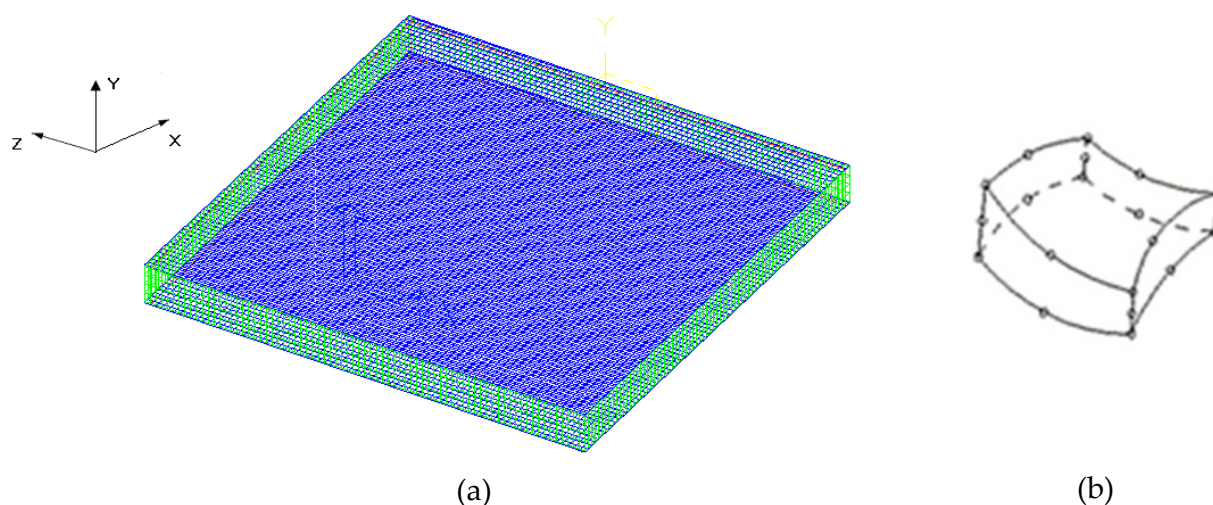
Figure 8. Illustration of a) Meshed quarter sandwich panel and b) Solid Brick Element (20 node brick element) used in mesh generation.

Since the analysis involves material non-linearity, a yield function or yield criteria needs to be defined for the model. Von Mises yield criteria and its associated flow rule is used in this analysis. Isotropic hardening is also used to describe the change of the yield criterion as a result of plastic straining. Only the core elements are assigned a yield function due to the assumption that only core yielding occurs throughout the loading process. The face sheets are assumed to remain elastic at all time; hence no yield function needs to be assigned to the face sheet elements. However the yield point of the face sheet material is fed to the software to be used as indicator for stopping the analysis.

3.2.1. FEM challenges

The following challenges are experienced:

- One of these challenges is extracting the element force and storing them in a file. This problem is solved by displaying the data on the screen and then copied and stored in a separate file for further analysis.
- Identifying the nodes for a surface of interest so that they can be extracted from the file in which the elemental forces are stored. Since I-DEAS labels the nodes, the nodes corresponding to the surface of interest are copied and stored in a separate node labels file for further analysis.
- MATLAB program is developed to extract the elemental forces of the surface of interest from the file in which they are stored by matching the node labels of the surface that are stored in node labels file.
- Singularity is a serious problem. The post processing analysis for the quality of the elements is utilized to identify the poor elements. The problem is solved by refining the element size.

3.2.2. Advantages of FEM

The following are some advantages of using FEM over other methods:

- FEM is capable of capturing the problem details with little approximations compared to the analytical techniques.
- FEM provides solution for many problems like the current case that they do not have analytical solution.
- FEM method is cheap compared to the experimental models. There is no need to produce a prototype or to have high tech facility to conduct the investigation.
- There is no need for the investigator to be available in a certain place to perform the investigation.
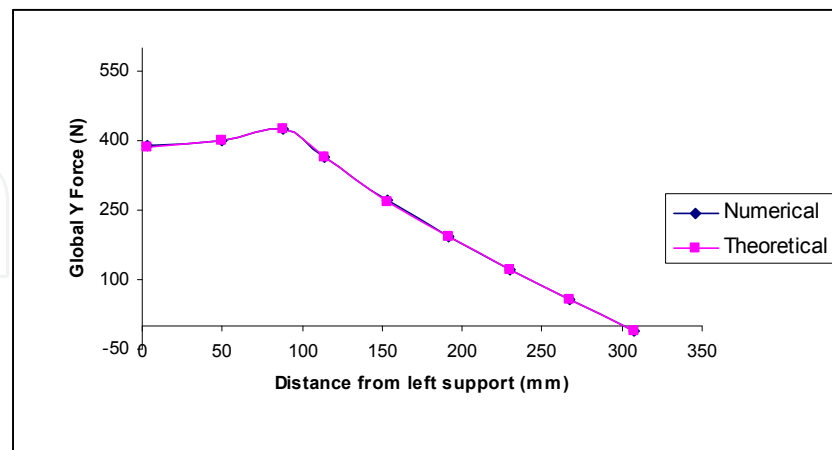
3.3. FEM verification

The finite element model is verified analytically and experimentally. The analytical verification is based on the classical sandwich panel theory whereas the experimental investigation is carried out for selected cases.

3.3.1. Analytical verification

Classical sandwich theory has been utilized to obtain close form solution (Zenkret, 1995). The comparison between the numerical and theoretical models in the linear rang are presented in Figure 9. The Figures show very good agreement between theoretical and numerical solution. The classical sandwich plate theory is therefore used to compare and validate the FEM predicted shear distribution of the panel in the linear range. Comparison between the FEM determined shear distribution and the classical sandwich plate theory distribution is performed at all load steps. It is assumed that is the core in the linear range carries the entire shear load. Results obtained from the closed form solution are compared with the total resultant shear load in the global Y direction, R_{TOT} (Y_g), obtained numerically using MATLAB.

Sample of the total shear resultant comparisons between the numerical and theoretical models in the linear rang are shown Figure 9a and 9b for load of 17.2 kPa and 51.7 kPa respectively.

(a)
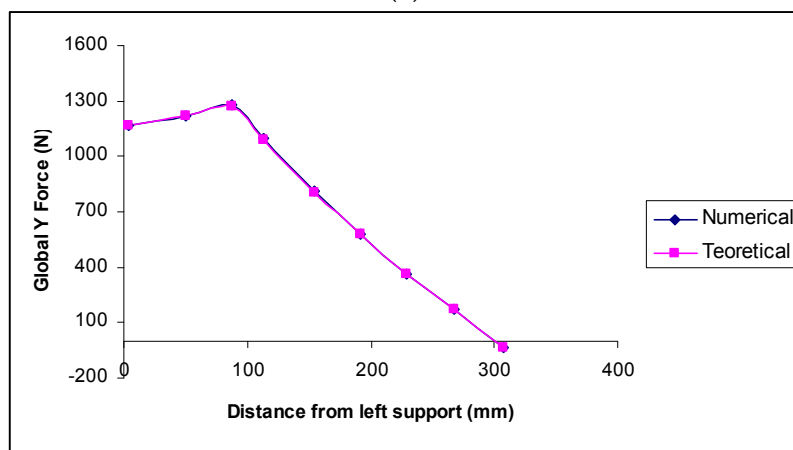
(b)

Figure 9. Total plate shear distribution comparison along X-axis at a) 17.2 kPa and b) 51.7 kPa.

3.3.2. Experimental verification

To assure accuracy and validity of the results some selected cases are investigated experimentally. The results obtained from the FEM are compared against those obtained experimentally. Both results show excellent agreement.

3.3.2.1. Test setup

Here is a description of the experimental setup used in the study and consists of the following:

1. The core of the sandwich panel is made of polyurethane foam. Top and bottom sheets of the sandwich panel are made of steel. The dimension of the panels used in the investigation is 250X250 mm². Mechanical properties of the sheet metal are obtained experimentally.

2. Fixture for applying simply supported boundary condition is produced. Figure 10 shows two different views of the fixture.
3. The test is performed on a uniaxial testing machine that is shown in Figure 11.
4. Distributed load is applied to the specimen by adaptors manufactured for this purpose. Figure 12 illustrates the adapters used in experimental setup.

(a)   (b)
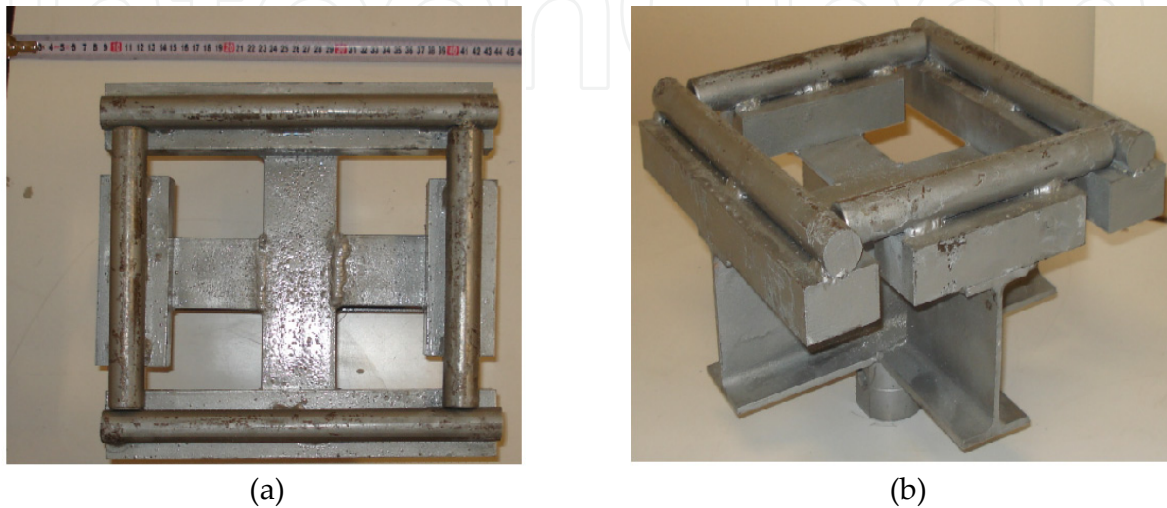
Figure 10. Pictures of the fixture that is produced for applying simply supported boundary condition, a) top view and b) 3D view.

(a)   (b)
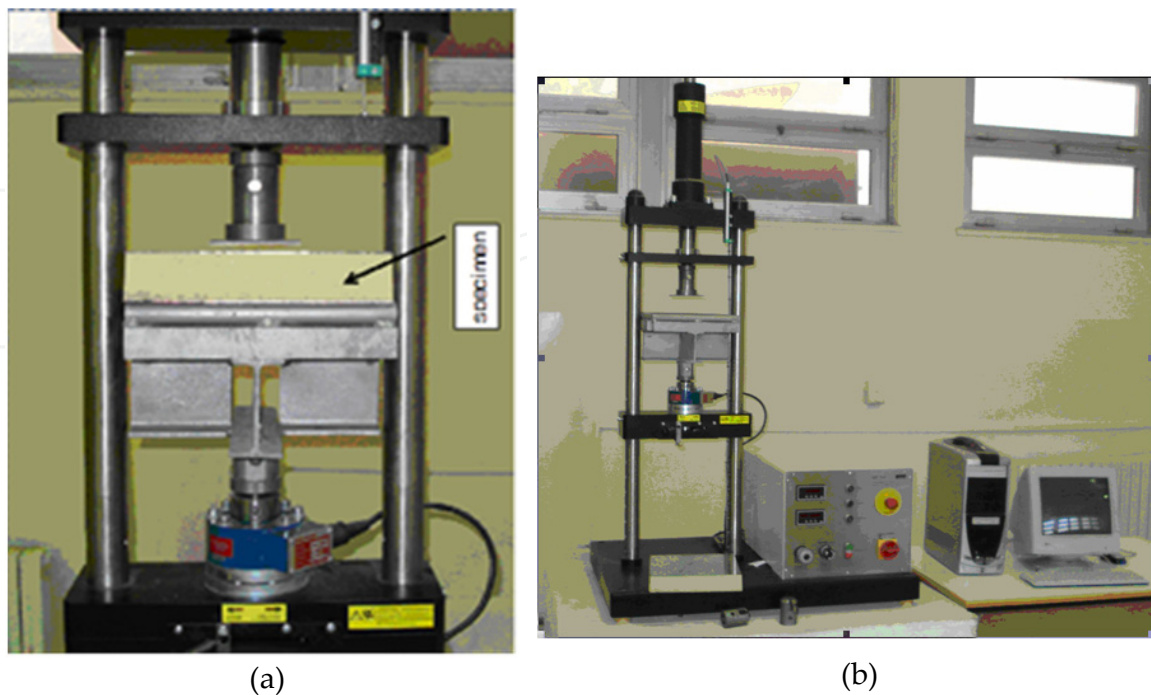
Figure 11. Uniaxial testing machine a) with specimen and b) without specimen
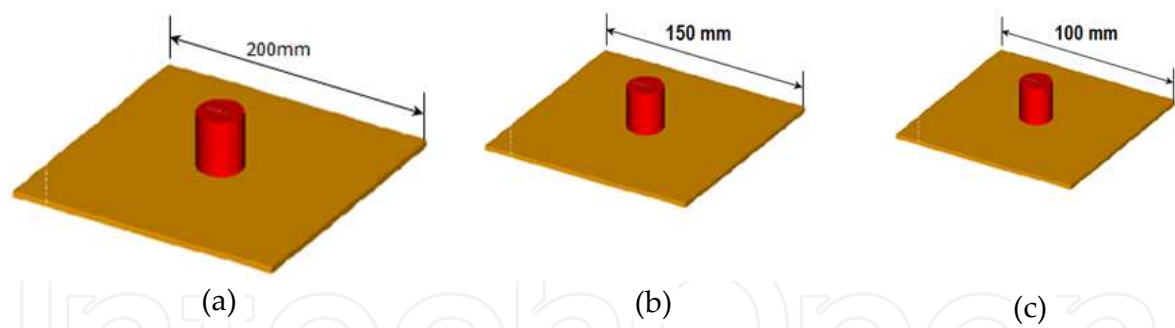
Figure 12. The adapters used in the experiments for applying distributed load on specimen of side length a) 200mm, b) 150mm and c) 100mm.

3.3.2.2. Mechanical properties of the specimen

The sandwich panel is made of polyurethane foam and steel sheets. The mechanical properties are obtained experimentally for both the sheets and the core. ASTM Designation: C 365 – 00 used for testing the core material whereas ASTM Designation: D 638 – 00 used for testing the sheets.

3.3.2.3. Analysis

The relation between the applied load and the deflection of the specimen center point are shown in Figures 13 and Figure 14 that present a comparison between the experimental results and FEM results. It may be seen that the results are in very good agreement.

To assure accuracy of the experimental results, the experiment is performed many times and the average values are plotted. The variation in the experimental results dose not exceeds 7% of the average value.
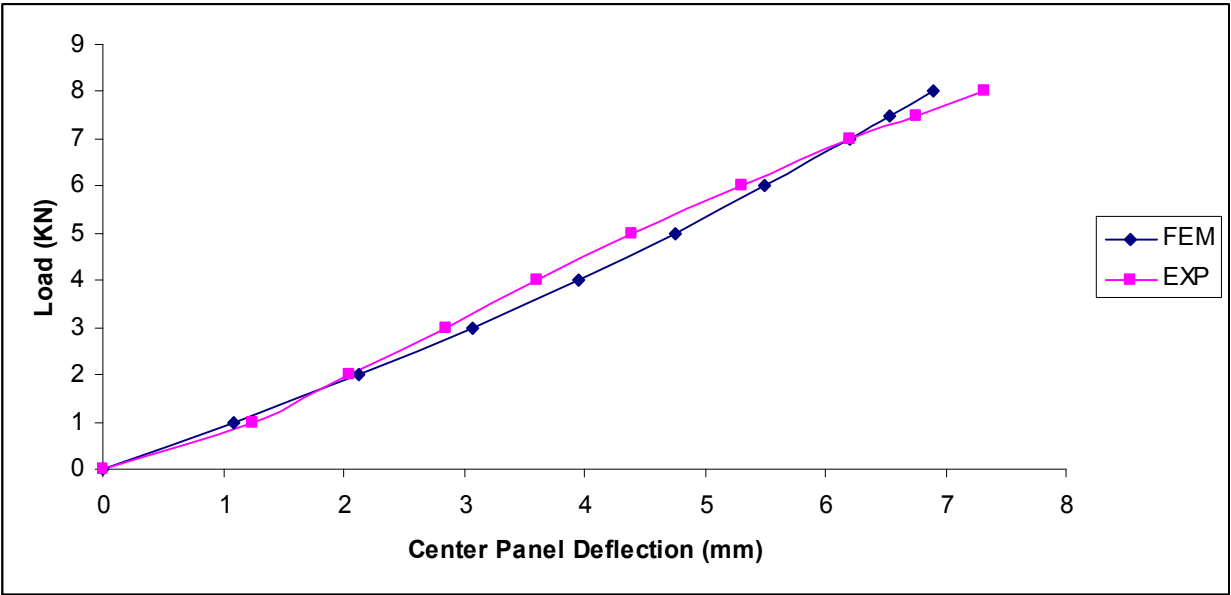
Figure 13. Comparison of load versus center deflection for core thickness = 49 mm, Sheet Thickness = 0.5 mm, applied load area = 200 X 200 mm².
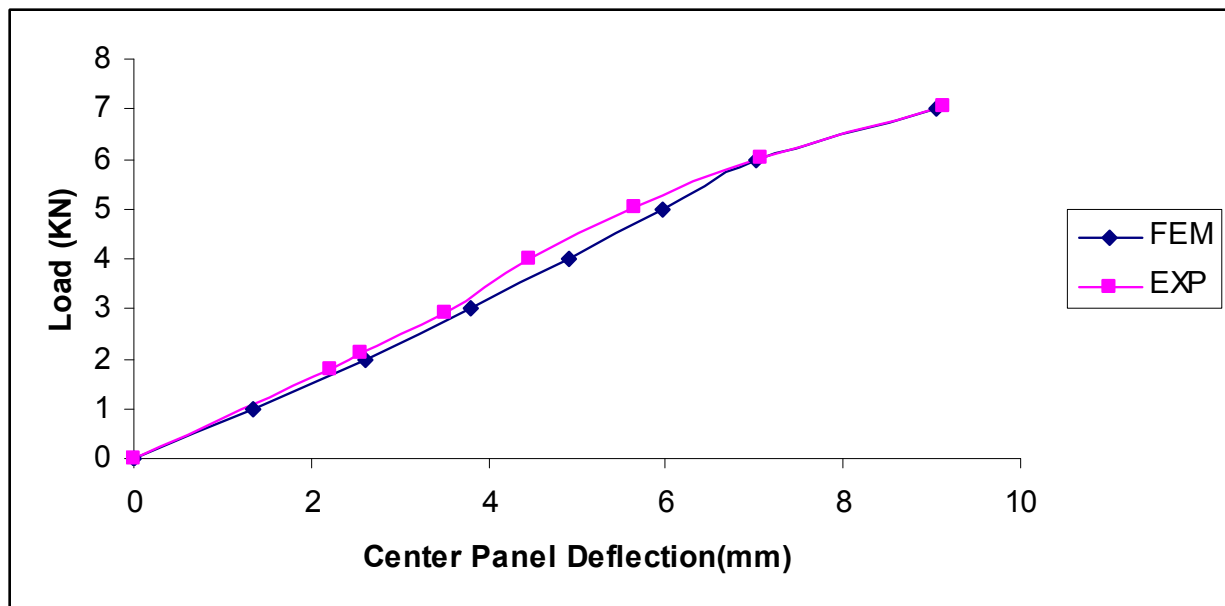
Figure 14. Comparison of load versus center deflection for core thickness=71 mm, sheet Thickness = 0.5 mm, applied load area = 150 X 150 mm².

4. Results

The main advantage of these results over the sandwich panel theory is that both geometric and material nonlinearities are considered without approximation. Usually these approximations eliminate part of the problem physics. By utilizing "I-DEAS' post processing module, stress and its all components, strain and it is all components including the plastic strain, and deformations are obtained.

Figures 15a and 15b present Von Mises stress contours for both panel and core respectively whereas Figures 16a and 16b present the plastic strain for both panel and core respectively. It is clear from Figure 16a and 16b that the plastic deformation occurs close to the panel support (close to the area where boundary conditions are applied).

The criterion, which is adopted by this investigation at what load step the FEM should stop the analysis, is when any of face sheets starts to yield or core material reaches fracture limit. This criterion fulfills the need of the designer; in general design engineer tries to avoid panel face sheets permanent distortion. As soon as the face sheet metal starts to yield, this means that permanent deformation is taking place. So all results produced neither exceed the loading that could cause face - sheet yielding nor exceed core fracture limit.

Figure 17a present the effect of loading area (area on which the load is applied) for core material A. It is obvious as the loading area increases the stress decreases for the same amount of loading. Same thing can be said for the bottom face sheet in Figure 17b. The core material (Figure 17a) reaches yield at low loads when the loading area is small.

The effect of loading area at sandwich panels of cores A, B, C and D (see Table 2) are presented 18 through 21. The maximum shear stress of each core in these graphs is

normalized by the maximum shear yield strength of its corresponding core material and the loading area is normalized by the total surface area of the panel. Also the shear stress of the face sheets is normalized by the corresponding shear yield strength of the face sheets. It can be seen from Table 2, the core materials are labeled from A to D in ascending order according to their stiffness. It is obvious from Figures 18 through 21 that the load carrying capacity of sandwich panel increases by increasing core stiffness. It is observed through all the results that the lower face sheet reaches yield limit before the top face sheet so in the Figures 18 through 21 the lower face sheet is presented. The results of this work are generated according to the univariate search optimization technique (Chapra and Canal, 2006).

(a)

(b)
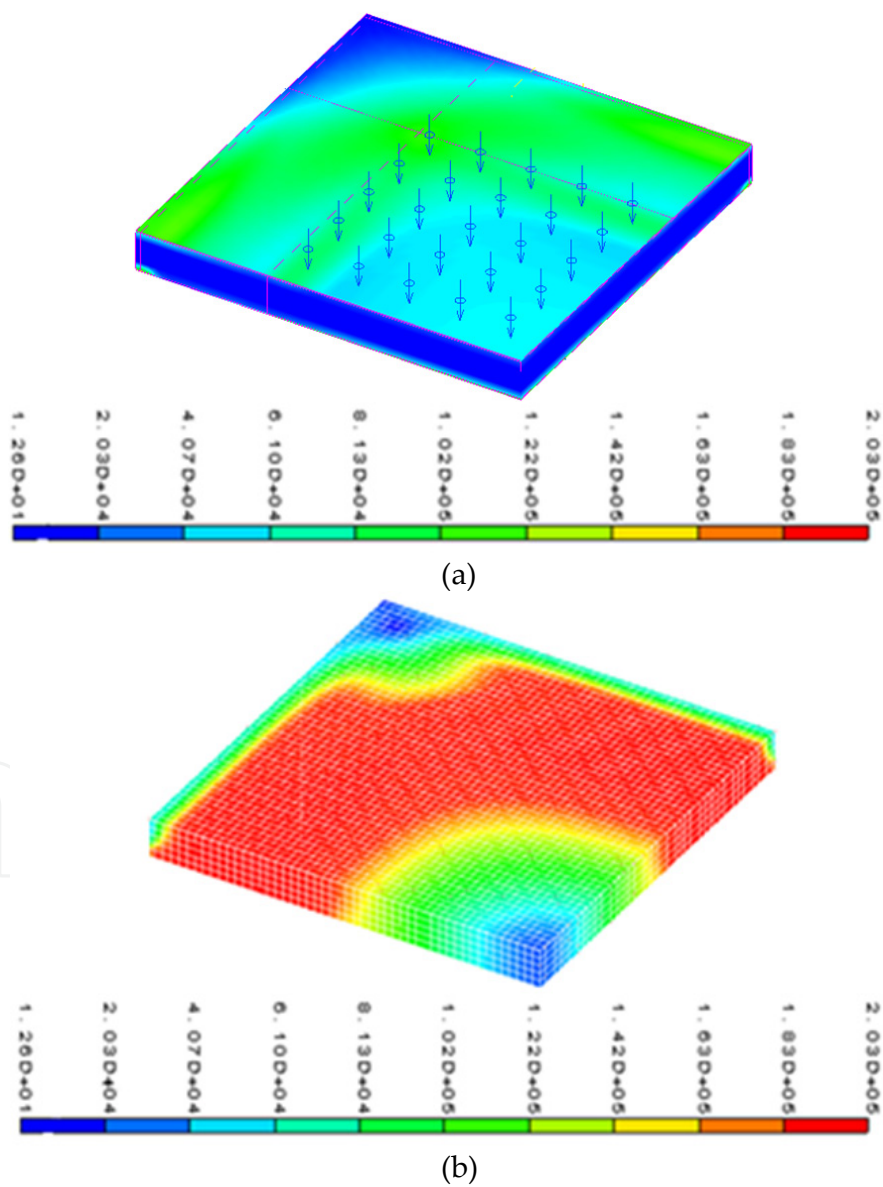
Figure 15. Von Mises stress contour (in MPa) for panel A of loading area 4/36 at load step 145kPa for a) the whole panel and b) the core of the panel.

(a)

(b)
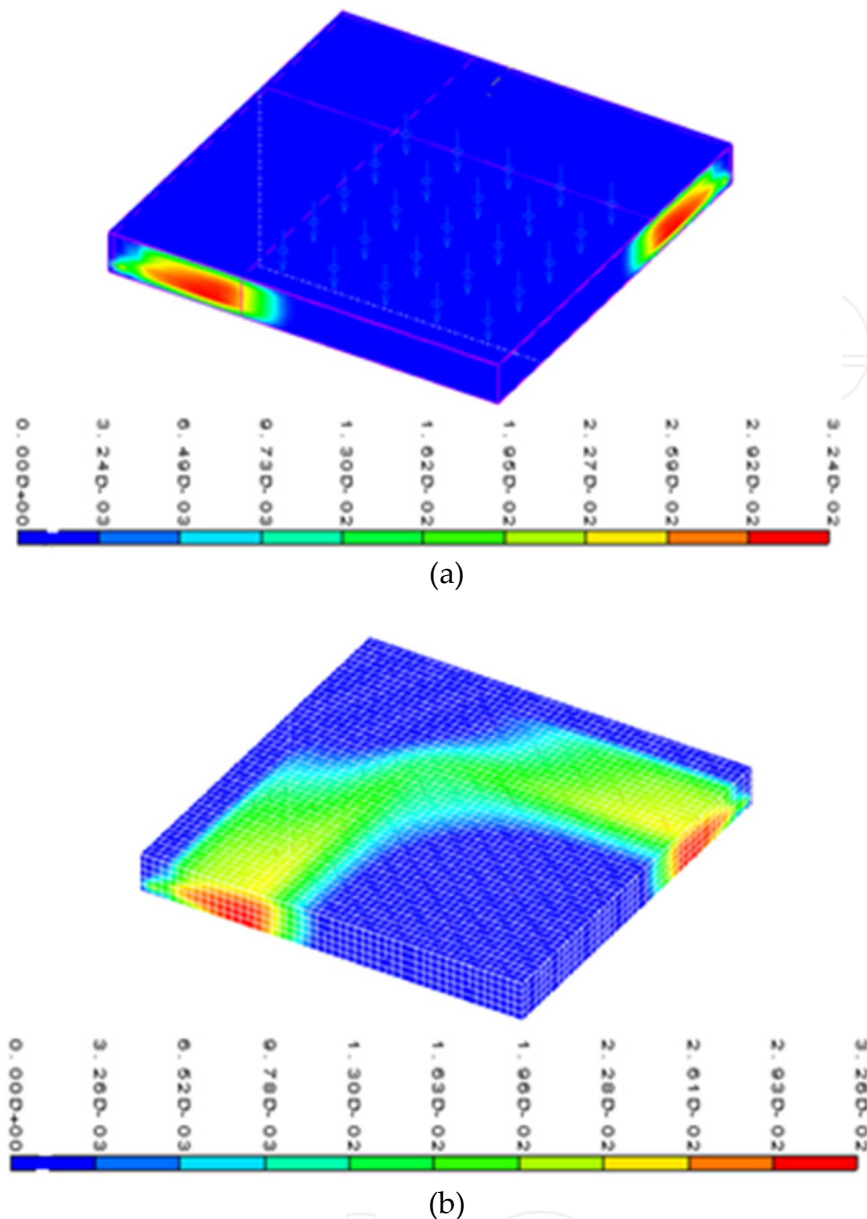
Figure 16. Demonstration of the plastic deformations contour for panel A of loading area 4/36 at load step 145 kPa for a) the whole panel and b) the core of the panel.

5. Discussion

As illustrated in Figure 16, the face sheet material starts to yield (entering the plastic range) close to the support (where the boundary conditions are applied). This is physically true, the distributed load over the loading area becomes concentrated reaction force on the strip area on which the boundary conditions (simply supported boundary condition) are applied, i.e., distributed load is converted to concentrated load. So the area where the boundary conditions are applied reaches the yield stress range before any other part of the panel.

As the loading area decreases the load is getting closer to the concentrated load, this is why in Figure 17 panel A of area ratio 1/36 reaches yield (plastic range) at lower load, than the

other panels presented in the Figure. Increasing the loading area increases the load carrying capacity of the panel.
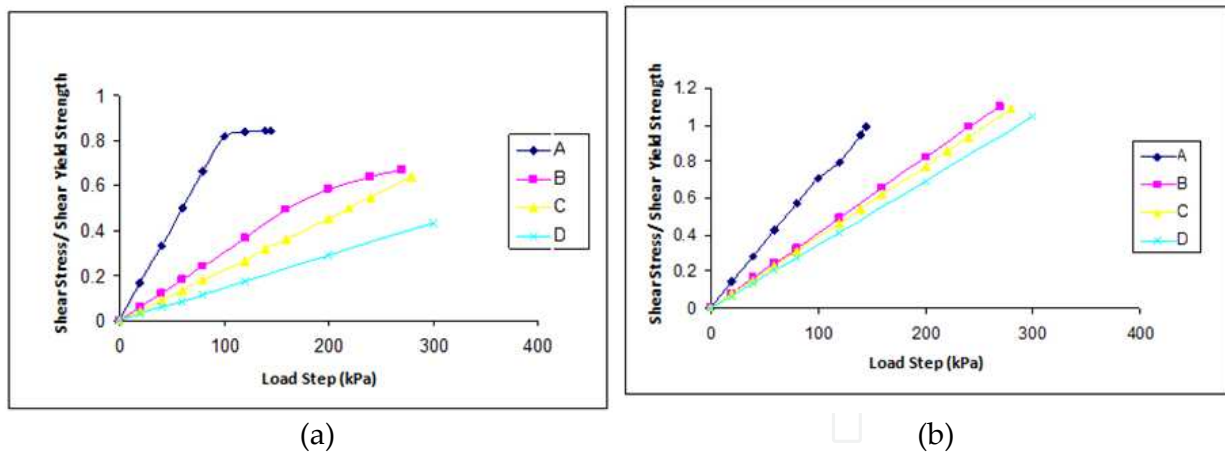

(a)   (b)
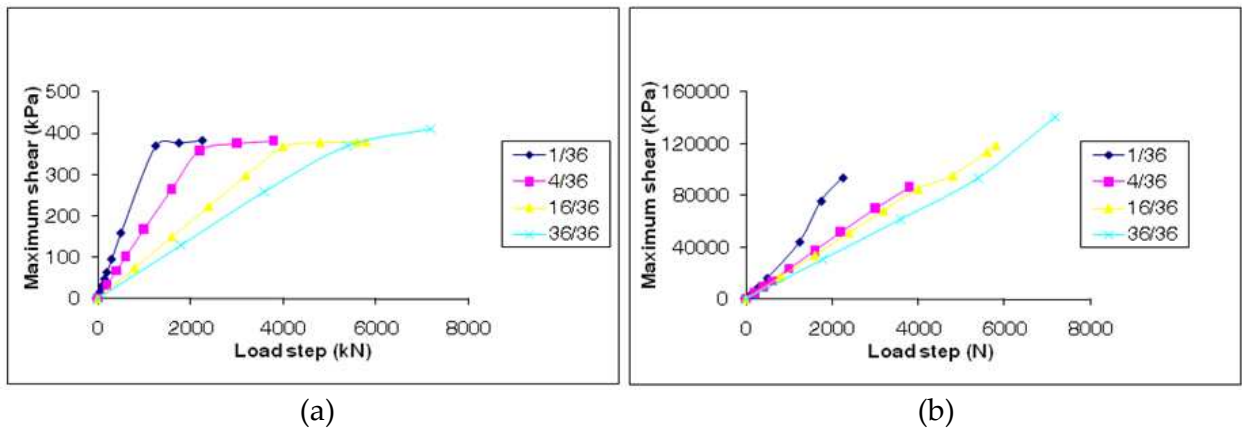
Figure 17. Presentation of panel A maximum shear stress versus loading for different load area ratio for a) Core and b) Lower Sheet.
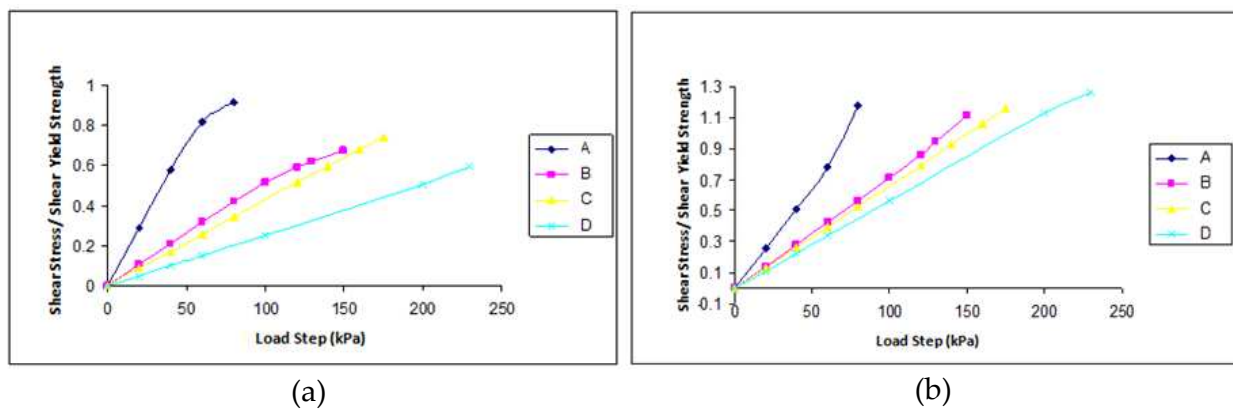

(a)   (b)
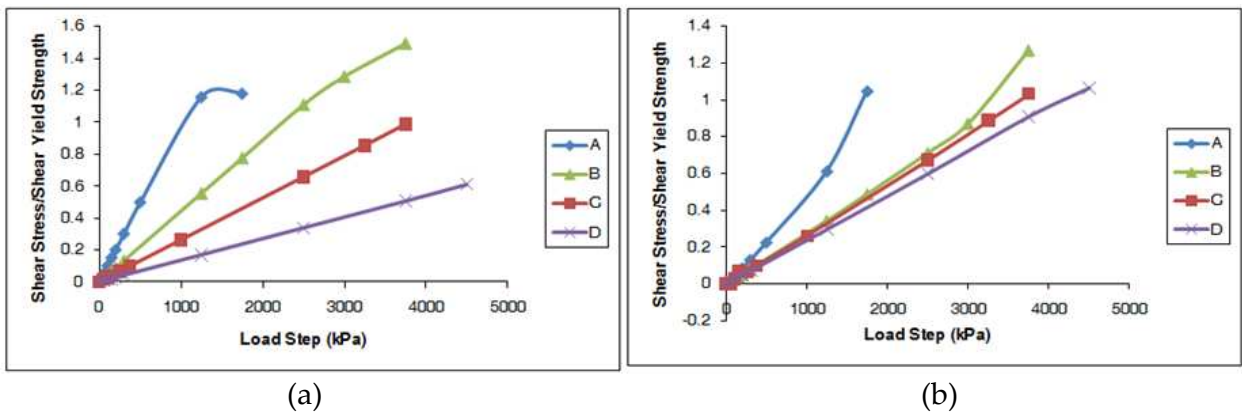
Figure 18. Presentation of maximum shear stress versus loading for A, B, C, and D core material panels of load area ratio 1/36 for a) Core and b) Lower Sheet.

(a)   (b)
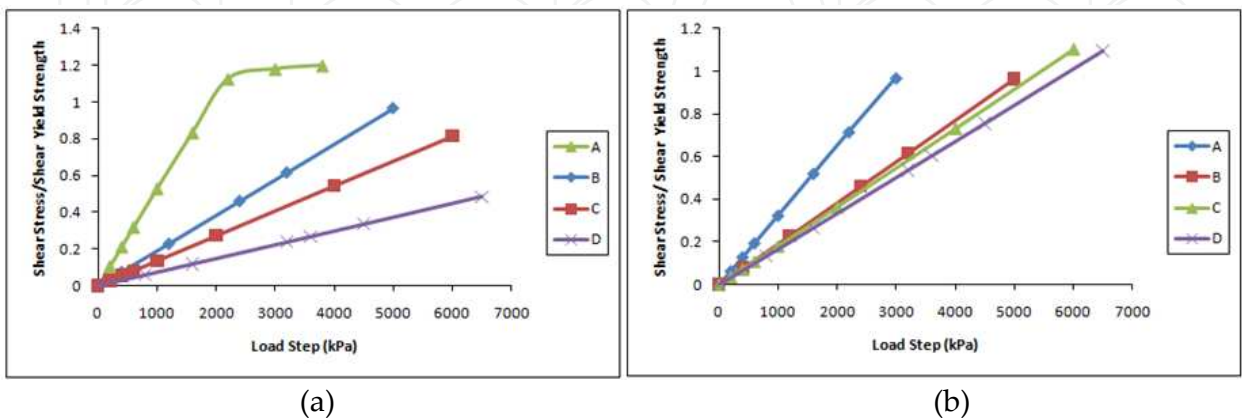
Figure 19. Presentation of maximum shear stress versus loading for A, B, C, and D core material panels of load area ratio 4/36 for a) Core and b) Lower Sheet.

Figure 20. Presentation of maximum shear stress versus loading for A, B, C, and D core material panels of load area ratio 16/36 and core thickness 30mm for a) Core and b) Lower Sheet.

Figure 21. Presentation of maximum shear stress versus loading for A, B, C, and D core material panels of load area ratio 36/36 for a) Core and b) Lower Sheet.

Figure 19 through 21 present that the lower face sheet for core material B, C and D reaches yield limit before their corresponding core material. This can be referred to the high stiffness of its core material, i.e., the panel gets closer in its behavior to isotropic plate.

It is obvious from Figure 17 through 21 that panel carrying capacity increases beyond core yield limit. In yield range the core material keeps deforming while the stress is constant (see Figure 22). This deformation works as a mechanism for transferring the excess load to the face sheets. For example in Figure 20, the shear stress of core material A after 100kPa load does not change whereas the shear stress of the corresponding lower face sheet keeps increasing.
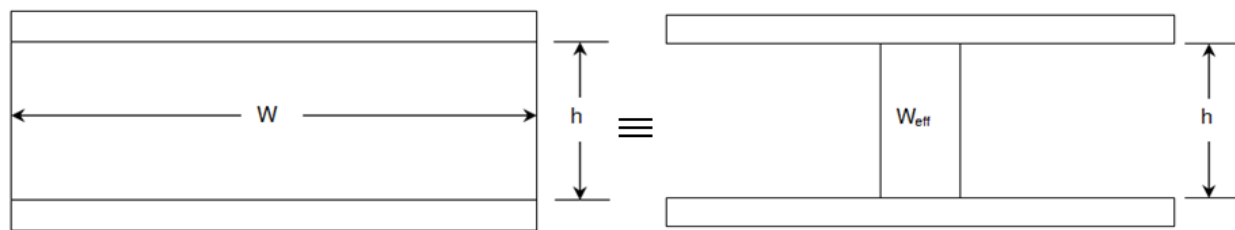
To replace the core material with same material of the top and bottom sheets, core's width should be shrunk according to the ratio of the modulus of elasticity of the core to that of the metal. The materials B, C and D are relatively stiff in comparison with A. Equivalent cross-section of core material (see Figure 23) has the same height for all cases and the width is increasing according to the modulus of elasticity ratios. For a rectangle the second moment of area ($wh^3/12$) is varying linearly with the width (equivalent width). The effect of the

difference between the materials B, C, and D is relatively small. So the stress curves for these panels are close to each other and the differences are small as it can be seen in Figures 17 through 21.
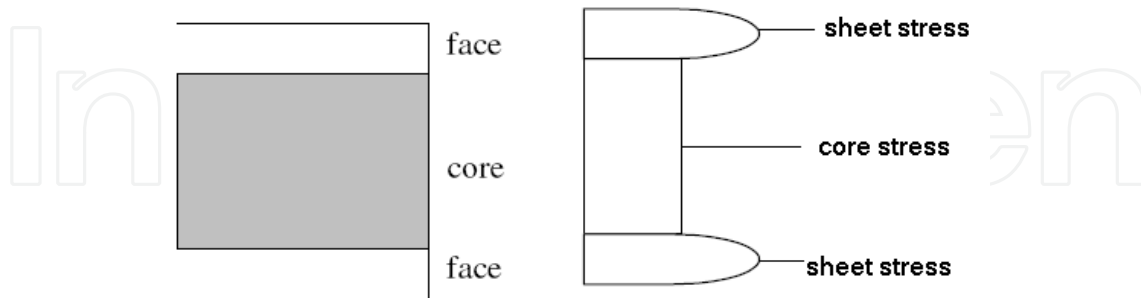
Figure 22. Schematic drawing of the shear stress for both face sheets and the core within plastic range.

Figure 23. Equivalent cross-section of core material with the same height

6. Conclusions

- Investigation of sandwich panel behavior beyond core material yield is carried out. The investigation is accomplished in sight of the core material nonlinearity and the geometric nonlinearity of the whole panel. High tech software 'I-DEAS' (Integrated Design Engineer Analysis software) is utilized to carry out the investigation.
- Finite element model is generated using 'I-DEAS' software. This model is validated against experimental and analytical cases available in the literature. To assure model accuracy experimental investigation for selected cases is carried out and compared with FEM. The model shows very good agreement with the analytical as well as the experimental one.
- It is proved that the load carrying capacity of sandwich panel can be improved by loading the panel beyond the core yield limit. This load is going to be transmitted to the face sheet.
- Increasing the stiffness of the core material to a certain extent leads to face sheet yielding before the core material. It is proved that increasing core stiffness increases the load carrying capacity of the sandwich panel.
- Loading area plays good roll in the load carrying capacity of sandwich panel. Distributing loads over large area of panel surface leads to higher load carrying capacity.

7. Recommendations

The following are recommendations for further extension of the FEM analysis:

- Investigate the bonding between the face sheets and the core after yielding.
- Modeling face sheets other than metal face sheets such as fiber composite materials
- Extending the FEM to include the bonding strength between the face sheets and the core so the relative dominance of core shear failure, face sheet yielding, or face sheet delamination could be determined.

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