Abstract— This paper describes analysis of low velocity transverse impact on fully backed sandwich beams with composite faces from Eglass/epoxy and cores from Polyurethane or PVC. Indentation on sandwich beams has been analyzed with the existing theories and modeled with the FE code ABAQUS, also loadings have been done experimentally to verify theoretical results. Impact on fully backed has been modeled in two cases of impactor energy with SDOF model (single-degree-of-freedom) and indentation stiffness: lower energy for elastic indentation of sandwich beams and higher energy for plastic area in indentation. Impacts have been modeled by ABAQUS. Impact results can describe response of beam in terms of core and faces thicknesses, core material, indenter energy and energy absorbed. The foam core is modeled using the crushable foam material model and response of the foam core is experimentally characterized in uniaxial compression with higher velocity loading to define quasi impact behaviour.

Keywords— Low velocity impact, Fully backed, Indentation, Sandwich beams, Foams, Finite element

I. INTRODUCTION

Sandwich structures are composed of composite laminates as skins and low density foam as core that present suitable properties for flexural stiffness and absorbing energy without weight penalty. These characteristics exhibit important role in impact loading. Impact response of sandwich structures are affected generally from two kinds of stiffnesses, flexural and contact stiffnesses of structures. Indentation loading can describe contact stiffness between indenter and beam and flexural stiffness is dependent to structure boundary conditions so can obtain it by three point loading.

In indentation of sandwich structures, foam has a weak resistance. Much research effort has been given to this problem in order to model a response of sandwich structures to local load. An excellent review article by Abrate [1] provides a through overview of research work on subject. Soden [2] also presented an analytical model for indentation of sandwich beam assuming plastic behaviour for core. Zenkert, et al [3] have recently studied indentation of sandwich beams. They presented an elastic-perfectly plastic compressive behaviour of foam core that elastic part of indentation is described by Winkler foundation model. Indentations on sandwich beams have been done experimentally and have been simulated with FE codes. Extensive applications of sandwich structures have been caused that researchers attend to their response of dynamic loadings


In this paper impact of fully backed sandwich beams have been modeled with SDOF model with contact stiffness, impactor energies have been chosen in two stages of lower and higher for elastic and plastic indentation on sandwich beams. Impact loadings have been modeled by ABAQUS. Results have been presented in terms of core and faces thicknesses, core material, indenter energies, absorbed energy and their effects on force and time of loading and impactor and beam displacement. Behaviour of core affects a principal influence in response of sandwich structures so cores have been loaded experimentally and accurately modeled in ABAQUS.

II. PROPERTIES OF BEAM COMPONENTS

A. FOAMS

In this research, PVC and Polyurethane foam were used in sandwich beams. These foams show a special behavior in uniaxial compression in according of Fig 1. The foam properties were obtained from uniaxial compression tests according to that given in ASTM D5308 standard [12]. Loading velocities were selected in two cases of 2mm/min and 100mm/min.
2mm/min is used for quasi static tests and 100mm/min is used for quasi impact tests. Experimentally foam properties are displayed in Table I.

![Figure 1. Foam behavior in uniaxial compression](image)

**TABLE I Mechanical Properties of Foams**

<table>
<thead>
<tr>
<th>Foam</th>
<th>v</th>
<th>$E_{20mm/min}$</th>
<th>$E_{100mm/min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>0.42</td>
<td>6.15</td>
<td>0.274</td>
</tr>
<tr>
<td>PVC</td>
<td>0.32</td>
<td>20.4</td>
<td>1.11</td>
</tr>
</tbody>
</table>

**B. Composite Laminate Properties**

Composite laminates were fabricated from Woven Eglass / epoxy in hand layup style. They were prepared in two forms of 2layers and 4layers and their properties were obtained from tests according to that given in ASTM D3039 standard [12]. Composite laminate properties are presented in Table II.

**TABLE II Mechanical Properties of composite laminate**

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>$E_1$</th>
<th>$E_2$</th>
<th>$G_{12}$</th>
<th>$G_{13}$</th>
<th>$G_{23}$</th>
<th>$E_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.92</td>
<td>11e3</td>
<td>62</td>
<td>8</td>
<td>8</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>0.52</td>
<td>14e3</td>
<td>130</td>
<td>12</td>
<td>12</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

**III. INDENTATION OF SANDWICH BEAM**

In this section, Abrate’s suggestion [1] and Zenkert’s approach [2] were chosen to introduce indentation of sandwich beams.

**A. Indentation Theory**

The model assumes an elastic Winkler foundation for the elastic core, and a perfectly plastic foundation for part of core that undergoes crushing, as schematically is shown in Fig2, [2].

**A.1 Elastic Solution**

When the load $P$ is small, the entire foundation is elastic and governing equation is

$$D_f \frac{d^4 w_{el}}{dx^4} + k w_{el} = 0$$

(1)

Where:

- $w_{el}$: face sheet deflection
- $k$: foundation modulus

**A.2 Perfectly Plastic Solution**

As the load increases, a part of core with length of $2a$ undergoes plastic deformation and core shows a uniform constant reaction $\sigma_p$ on the face sheet. Thus, governing equation is

$$D_f \frac{d^4 w_p}{dx^4} + \sigma_p = 0$$

(3)

Where:

- $\sigma_p$: plateau compressive yield stress

And boundary conditions are

$$w_p'(0) = 0, \quad w_p'(\infty) = \alpha, \quad w_p''(\infty) = 0, \quad w_p'(\infty) = 0$$

**B. Indentation Test in Sandwich Beams**

The properties of manufactured sandwich beams have been presented in Table III. Foam materials, skins thicknesses and foam thickness are varied between samples. Indentation has done experimentally with 20mm diameter indenter. Loading velocity was chosen 2mm/min. Sandwich beams have been supported on a rigid plate (Fig 3). Also indentation was modeled in Abaqus (Fig 4). Contact stiffness of beams was presented in Table III. Indentations curves are displayed in Fig 5 and 6 for several samples of sandwich beams introducing in Table 3. Results show suitable convergences.
IV. IMPACT ON FULLY BACKED SANDWICH BEAMS

In this loading, a rigid plate has been chosen for boundary condition that sandwich beams place on it and are loaded with a low velocity cylindrical indentor. In this state we can only use contact stiffness and eliminate flexural stiffness of sandwich beams. Impact loadings include indentation on sandwich beam so we used indentor in two states of energy loading: Lower energy for elastic indentation without residual indent after loading and higher indentor energy for plastic indentation. Mass and velocity of indentors with their energies have been presented in Table IV.

A. Elastic indentation

In according to fig 7. Impact loading have been modeled with a SDOF model with Eq (4) and contact stiffnesses of Table III for elastic indentation also it simulated in ABAQUS. Impact results was presented in fig 8 and a complete comparison between results of manufactured beams has been presented in Fig’s 9 and 10

B. Plastic indentation

There isn’t any accurate and suitable model for describing of unloading on sandwich beams so we used elastic contact stiffness for unloading to reach specified residual indent. In according to fig 11 [13], an experimental result of indentation and unloading have been presented that shows mentioned assumption isn’t inaccurate. In loading stage, equations (III) are used for indentation and in total time of impact, contact stiffness has been eliminated when there isn’t any indentation or any contact between indentor and beam. Plastic Impact results have been presented in fig’s 12, 13
TABLE III. Properties of used sandwich beams

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Sandwich beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50</td>
<td>30.5</td>
<td>30.5</td>
<td>30.05</td>
<td>30.5</td>
<td>Wide mm</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>Length mm</td>
</tr>
<tr>
<td>21.6</td>
<td>20.5</td>
<td>10.2</td>
<td>9.7</td>
<td>11.9</td>
<td>11.6</td>
<td>Thickness mm</td>
</tr>
<tr>
<td>PU</td>
<td>PU</td>
<td>PVC</td>
<td>PVC</td>
<td>PU</td>
<td>PU</td>
<td>Core</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>70</td>
<td>70</td>
<td>40</td>
<td>40</td>
<td>Core density Kg/m³</td>
</tr>
<tr>
<td>19.76</td>
<td>19.46</td>
<td>8.36</td>
<td>8.66</td>
<td>10.06</td>
<td>10.56</td>
<td>Core thickness mm</td>
</tr>
<tr>
<td>4layer</td>
<td>2layer</td>
<td>4layer</td>
<td>2layer</td>
<td>4layer</td>
<td>2layer</td>
<td>Composite skins</td>
</tr>
<tr>
<td>0.92</td>
<td>0.52</td>
<td>0.92</td>
<td>0.92</td>
<td>0.92</td>
<td>0.52</td>
<td>Skins thickness mm</td>
</tr>
<tr>
<td>400</td>
<td>244</td>
<td>1076</td>
<td>643</td>
<td>392</td>
<td>235</td>
<td>Elastic contact stiffness N/mm</td>
</tr>
</tbody>
</table>

TABLE IV. Indentor characteristic for elastic & plastic indentation

<table>
<thead>
<tr>
<th>Loading types</th>
<th>Energy (J)</th>
<th>Velocity (m/s)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>0.03</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>II</td>
<td>0.12</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>III</td>
<td>0.12</td>
<td>2</td>
<td>60</td>
</tr>
<tr>
<td>IV</td>
<td>0.01</td>
<td>2</td>
<td>5 (g/cm² wide)</td>
</tr>
<tr>
<td>Plastic impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1.2</td>
<td>2</td>
<td>600</td>
</tr>
</tbody>
</table>

\[ M_1 \ddot{X} + K_1 X = 0 \quad (4) \]

V. RESULTS

Assuming elastic indentation for impact loading and according to fig 8, it can be calculated that SDOF theory shows higher values than Abaqus results for impact force and loading time, that it are resulted from approximation in calculating contact equations and mass-spring model assumption. However results present suitable following to each other in impact time. Fig 8 present that indentor displacement is larger for SDOF results.

Comparison between indentor energies show that:
Increasing in indentor mass is caused increasing for force and time of impact and indentor displacement increasing but increasing in velocity of indentor results increasing in impact force and displacement but don’t show any important change in loading time. For loadings with similar indentor energies like state II, III (in table IV), results show a little difference in maximum impact force that they are very close to each other.

Fig 9 shows response of beams that have been presented in table III, they have been modeled with SDOF and similar indentor energies of IV from table IV for all of them. Also this comparison have been done in ABAQUS and indentor velocities presented in fig 10.
Results show that increasing of foam thickness is caused increasing in loading time and indentor displacement but it involves decreasing in impact force and indentor velocity changing. Lower change in indentor velocity shows decreasing in absorbed energy of indentor.

Increasing of foam stiffness shows decreasing in loading time, indentor displacement and absorbed energy but it cause increasing in impact force. Increasing of skin stiffness shows decreasing in loading time and indentor displacement but presents increasing in impact force.

But don’t have any effect on absorbed energy for elastic impact. Fig 12 shows that for V loading type, indentation goes to plastic area on sandwich and certainly residual indent will happen. In this state beam doesn’t go to initial position, so contact between indentor and beam will be cut earlier in return indentor stage. In plastic indentation SDOF theory behave in a very good following with FE results in loading step but in return, assumption of elastic contact and residual indent make some differences between results.
VI. CONCLUSION

Knowing and modeling of foams behavior have an important role in prediction of sandwich structure responses. In indentation on sandwich beams, presented theory shows proper behavior comparing with test and FE results that present a suitable model for contact stiffness defining. For modeling of impact SDOF model shows structure behavior in a good approximation with FE results. Contact stiffness is only source of resistance in impact, so using of single-degree-of-freedom model is acceptable and satisfactory. Indentation of impact can be divided in two stage of elastic and plastic area.

In elastic impact loading, changing in foam and skins thickness, stiffness have an important effect in behavior of sandwich structure for time, force, displacement and absorbed energy in impact loading.

In plastic impact loading, SDOF results converge greatly with FE in loading area but in unloading, mentioned assumption make differences between results, so results behave similar and with each other in this area.

REFERENCES