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Homogenization Model for the Folded Core Sandwich Plates under the Transverse Loading

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Abstract: - In the development of engineering science, material engineering plays a pioneering role. In the use of material, the proper use of the structure also brings to the great efficiency. Composite materials, especially composite sandwich panels have shown outstanding advantages in many fields in engineering, therefore, the calculation to determine their mechanical behavior is very necessary. There have been many authors suggesting methods for calculating sandwiches, but with large and unsymmetrical sandwich panels, these methods are still very difficult. In this paper, we present a method to build an equivalent model (2D) that can be used to determine mechanical behavior of sandwich panels and replaces to original model (3D). This work helps to significantly reduce the computational time as well as time to build the geometry of model. To demonstrate the performance, in this work, we carry out the simulation of folded core sandwich in case of transverse loading. This method can be used, of course, for any type of folded core as well as many types of sandwich panels.

Keywords: Folded core, Homogenization, Orthotropic plate, Sandwich panels, Transverse shear

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I. INTRODUCTION

Nowadays, structural sandwich panels are widely used and they play an important role in many industrial areas because of their good compromise between stiffness and lightness. Sandwich panels are often formed by adhering two high-density thin plates called face sheets with a low-density core possessing less strength and stiffness. We can obtain various properties and desired performances, especially high strength to weight ratio by varying the core materials, core structures and core thickness, or material of face-sheets. Many different core shapes have been applied to the construction of sandwich structures such as folded, solid, foam, truss, and web core. Folded core sandwich is one of the most used materials to make partitions or roof skin construction or automobile. The folded core sandwich plate is produced by a manufacturing process, in which three or more layers are laminated together. The flat layers are called liners and the folded cores are referred to as flutes (Fig. 1). The manufacturing process gives three characteristic directions: The machine direction (MD), the cross direction (CD), and the thickness direction (ZD).

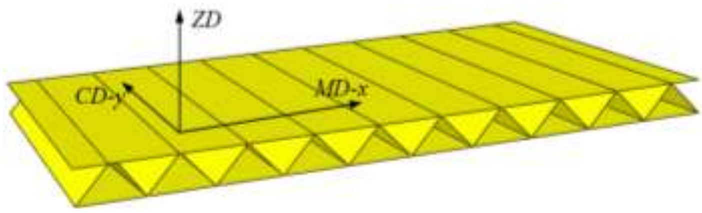

Fig. 1. The model of sandwich plate with folded core

Several approaches to the modeling of these sandwich panels are discussed, in which finite element method is known as an effective method and used popularly [1]. When we use the finite element in the commercial software, an actual geometry of the model is represented [2]; however, this method can be easily done with a tiny, normal size and symmetrical plates. In fact, the sizes of these plates are usually large and unsymmetrical, thus building model will be difficult and demand high computer cost as well as long calculation time. Several authors proposed to use an equivalent continuum instead of the core (honeycomb core, for example), and then combine it with a 3D model [3] or a bi-dimensional plate model [4]. To determine its mechanical behavior, we can always completely discretize the core and facings by shell elements (3D shell modelling), but the modelling will be extremely tedious and time-consuming. It is much more advantageous to homogenize the sandwiches in order to obtain an equivalent orthotropic plate (2D plate or shell modelling) [5].

Many homogenization models were obtained by analytical, numerical and experimental methods [5-13]. Luo et al. [6] made an analytic study on the bending stiffnesses of corrugated board. Nordstrand et al [7-9] presented some homogenized properties of the corrugated board by an analytical method. They have studied the buckling and post-buckling behaviors of an orthotropic plate including the transverse shear effect. Aboura et al. [10] also developed an analytical homogenization model based on the theory of laminated plate and compared its results with numerical and experimental results. Buannic et al. [11] proposed a homogenization theory based on the asymptotic expansion method and presented the FE computation of the effective behavior properties. Biancolini [12] used a FE numerical approach for evaluating the stiffness parameters. Among the existing analytical models, there are still some questionable problems such as the behaviors under the transversal shear efforts and the torsion moments.

In this paper, we present a homogenization model to simulate the mechanical behaviors of folded core sandwich panels. The homogenization is carried out by calculating analytically the global rigidities of the folded core sandwich and then this 3D structure is replaced by an equivalent homogenized 2D plate. The simulations in case of transverse loading of Abaqus-3D and H-2D model for the folded core sandwich will be studied in this article. This 2D homogenization model is very fast and has close results comparing to the 3D model using the Abaqus shell elements. The comparison shown many outstanding advantages of proposed model such as reduced time for modeling, time for calculation … We can use this model, of course, for other core structures, types of load or many other types of sandwich panels.

II. MINDLIN'S THEORY AND THEORY OF LAMINATED PLATE

Mindlin's theory and theory of laminated plates are often used in many problems to calculate and analyze the behavior of composite structures. The membrane forces, bending, torsional moments, and transverse shear forces are obtained by integration of the constraints on the thickness.

$$\{N(x,y)\} = \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix} dz \tag{1}$$

$$\{M(x,y)\} = \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} z \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix} dz \tag{2}$$

$$\{T(x,y)\} = \begin{bmatrix} T_x \\ T_y \end{bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{bmatrix} \sigma_{xz} \\ \sigma_{yz} \end{bmatrix} dz \tag{3}$$

If we consider a composite panel consisting of several layers, the resulting forces defined above may be combined in layers:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} dz = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix}_k \left(\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix}_m + z \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \right) dz \tag{4}$$

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} z\,dz = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix}_k \left(z \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix}_m + z^2 \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \right) dz \tag{5}$$

$$\begin{Bmatrix} T_x \\ T_y \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_{xz} \\ \sigma_{yz} \end{Bmatrix} dz = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{bmatrix} C_{11} & 0 \\ 0 & C_{22} \end{bmatrix}_k \begin{Bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} dz \tag{6}$$

After the integration along the thickness, we obtain the overall stiffness matrix that links the generalized deformations with resultant forces:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \\ T_x \\ T_y \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & 0 & 0 & 0 \\ A_{12} & A_{22} & 0 & B_{12} & B_{22} & 0 & 0 & 0 \\ 0 & 0 & A_{33} & 0 & 0 & B_{33} & 0 & 0 \\ B_{11} & B_{12} & 0 & D_{11} & D_{12} & 0 & 0 & 0 \\ B_{12} & B_{22} & 0 & D_{12} & D_{22} & 0 & 0 & 0 \\ 0 & 0 & B_{33} & 0 & 0 & D_{33} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & F_{11} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & F_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xm} \\ \varepsilon_{ym} \\ \gamma_{xym} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} \quad (7)$$

in which

$$\begin{aligned} A_{ij} &= \sum_{k=1}^{n} \left[h^k - h^{k-1} \right] Q_{ij}^k = \sum_{k=1}^{n} Q_{ij}^k t^k \\ B_{ij} &= \frac{1}{2} \sum_{k=1}^{n} \left[\left(h^k \right)^2 - \left(h^{k-1} \right)^2 \right] Q_{ij}^k = \sum_{k=1}^{n} Q_{ij}^k t^k z^k \\ D_{ij} &= \frac{1}{3} \sum_{k=1}^{n} \left[\left(h^k \right)^3 - \left(h^{k-1} \right)^3 \right] Q_{ij}^k = \sum_{k=1}^{n} Q_{ij}^k \left[t^k \left(z^k \right)^2 + \frac{\left(t^k \right)^3}{12} \right] \\ F_{ij} &= \sum_{k=1}^{n} \left[h^k - h^{k-1} \right] C_{ij}^k = \sum_{k=1}^{n} C_{ij}^k t^k \end{aligned} \quad (8)$$

The law of behavior above can be written in matrix form:

$$\begin{bmatrix} \{N\} \\ \{M\} \\ \{T\} \end{bmatrix} = \begin{bmatrix} [A] & [B] & [0] \\ [B] & [D] & [0] \\ [0] & [0] & [F] \end{bmatrix} \begin{bmatrix} \{\varepsilon_m\} \\ \{\kappa\} \\ \{\gamma_s\} \end{bmatrix} \quad (9)$$

where $\{N\}$, $\{T\}$ and $\{M\}$ are the internal forces and moments; $[A]$, $[D]$, $[B]$ and $[F]$ are the stiffness matrices related to the membrane forces, the bending-torsion moments, the bending-torsion-membrane coupling effects and the transverse shear forces respectively; $\{\varepsilon_m\}$ is the membrane strain vector, $\{\kappa\}$ is the curvature vector and $\{\gamma_s\}$ is the transverse shear strain vector.

III. HOMOGENIZATION MODEL FOR THE FOLDED CORE SANDWICH

The sandwiches with folded core are made of multilayer including face-sheets and core that have fluting cores and the cavities between layers. To apply the calculation method using the theory of plates, the matrix (9) obtained by the theory of laminated plates should be modified [10, 11]. Considering a folded core sandwich plate and using *a*, *b*, and *c* to represent the lower liner, the folded core and the upper liner (Fig. 2). To homogenize a folded core sandwich plate, we consider a representative volume element (RVE). We note that, this RVE must be small enough comparing to the size of the entire plate. According to the structure of the plate, we take out a period length of the core as a RVE. We calculate the average mechanical properties of RVE and use them to model this 3D structure by a homogeneous 2D plate. However, the folded core has a vertical position varies with *x* direction so we cut it into very little vertical slices (thickness *dx*) and integrate along the thickness (or sum up the participants of three layers) on each slice.

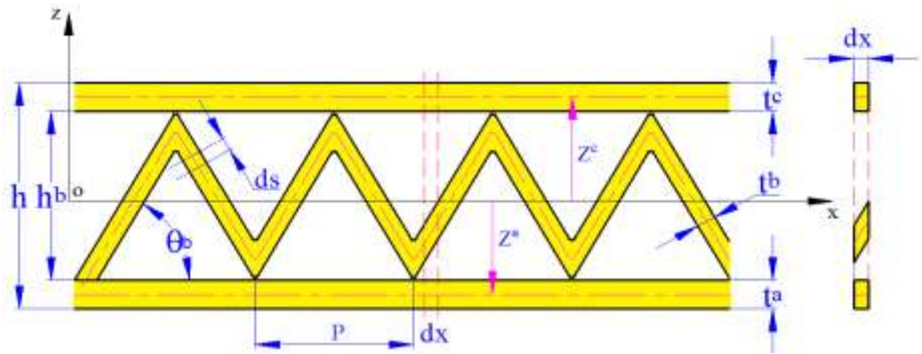

Fig. 2. Geometry of folded core plates

Noting that the mechanical properties of the core achieved by experiments are valid only in its face, so we need to calculate the local coordinate system. Once the overall stiffness of each slice is obtained by integrating over the thickness of the plate, homogenization along *x* will be performed to calculate the average stiffness of all slices in one period [5].

$$[A] = \frac{1}{P}\int_0^P [A(x)]\,dx \quad ; \quad [B] = \frac{1}{P}\int_0^P [B(x)]\,dx$$
$$[D] = \frac{1}{P}\int_0^P [D(x)]\,dx \quad ; \quad [F] = \frac{1}{P}\int_0^P [F(x)]\,dx \tag{10}$$

3.1 Traction and bending stiffnesses related to N_x, M_x, N_y, M_y

The vertical position (*z*) of a groove portion (*ds*) is a function of *x* and a thickness over its vertical section is a function of the angle of inclination of the groove. Eq. (8) can be write:

$$A_{ij} = Q_{ij}^a t^a + Q_{ij}^b \frac{t^b}{\cos\theta^b} + Q_{ij}^c t^c$$
$$B_{ij} = Q_{ij}^a t^a z^a + Q_{ij}^b \frac{t^b}{\cos\theta^b} z^b + Q_{ij}^c t^c z^c \tag{11}$$
$$D_{ij} = Q_{ij}^a\left[t^a\left(z^a\right)^2 + \frac{1}{12}\left(t^a\right)^3\right] + Q_{ij}^b\left[\frac{t^b}{\cos\theta^b}\left(z^b\right)^2 + \frac{1}{12}\left(\frac{t^b}{\cos\theta^b}\right)^3\right] + Q_{ij}^c\left[t^c\left(z^c\right)^2 + \frac{1}{12}\left(t^c\right)^3\right]$$

where

$$h = t^a + h^b + t^c$$

$$z^a = -\frac{h}{2} + \frac{t^a}{2}; \quad z^c = \frac{h}{2} - \frac{t^c}{2}; \quad z^b(x) = -\frac{h}{2} + t^a + \frac{2h}{P}x$$

3.2 Transverse shear stiffnesses related to T_y

In laminate theory, the shear stiffness relative to the shear force T_y on a CD section is calculated by the sum of the layers. However, the CD section of the sandwich is not a continuous medium and the transverse shear deformation is not constant or linear on the section, so the theory of laminates is no longer valid. The shear force T_y on a CD section causes a coupling between bending and transverse shear. Thus, it is very difficult to directly determine the transverse shear stiffness on a CD section relating to T_y.

To avoid the coupling between bending and transverse shear, and to obtain "pure" shear, according to the reciprocity theorem, Nordstrand et al. [7] have proposed a horizontal shear model in which transverse shear under the force T_y (force along *z* and per unit length along *x*) is replaced by shear over the thickness under the force *T* (along *y*) (Fig. 3). The shear modulus thus obtained is equivalent to the transverse shear modulus.

The deformations due to the shearing of the flat skins are much less than those due to the shearing of the groove, and therefore negligible. We make equivalence between one-half period of the folded core sandwich (with both skins not shown) (Fig. 3a) and a solid with a dimension of $P/2 \times b \times h$ (Fig. 3b). A pair of shear forces *T* exerted on the groove by the upper and lower faces gives the sliding *v*. The shear of the homogeneous solid can be defined by:

$$\tau_{zy} = \frac{T}{0.5Pb} = G_{zy}\frac{v}{h} \tag{12}$$

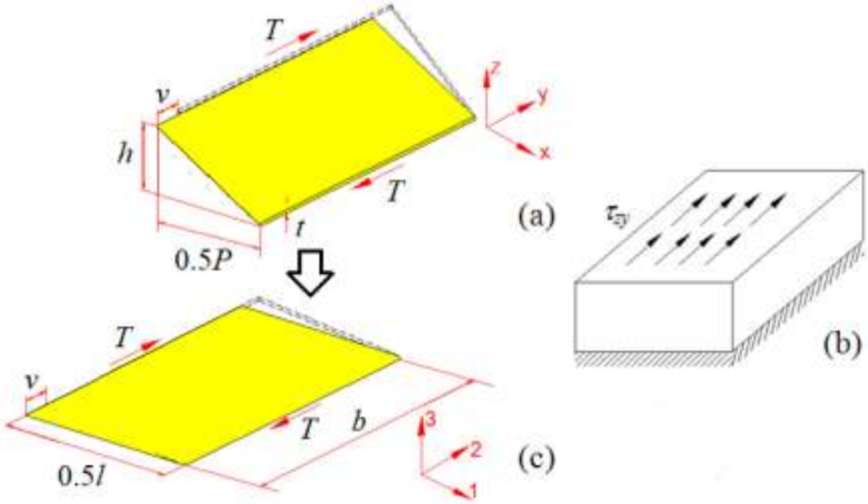

Fig. 3. The equivalent model to determine shear stiffness on CD section

The shear stress in the 3D folded core (Fig. 3a) is equivalent to the shear in the flattened groove (Fig. 3c). This gives us:

$$\tau_{12} = G_{12}\gamma_{12} \quad \Rightarrow \quad \frac{T}{bt} = G_{12}\frac{v}{0.5l} \quad \Rightarrow \quad v = \frac{0.5Tl}{G_{12}bt} \tag{13}$$

Substituting Eq. (12) in (13), we obtain the shear modulus of the solid:

$$G^*_{zy} = G_{12}\frac{4ht}{Pl} \tag{14}$$

Thus, we have the shear stiffness on CD section:

$$F_{22} = G^*_{zy}.h = \frac{G_{12}4t}{Pl}h^2 \tag{15}$$

3.3 Transverse shear stiffnesses related to T_x

In laminate theory, the transverse shear stiffness relative to the shear force T_x on MD section is also calculated by the sum of the layers. However, it is also difficult to determine this stiffness because of the coupling between the bending and transverse shear. Nordstrand et al. [7] proposed to replace the transverse shear under the force T_x (on MD section and along *z*) by shearing on the thickness under the force $T = T_x$ along *x*. In fact, this problem is not really a problem of shear of the three layers; it is dominated by the tension and compression of the folded core. The deformations due to the shearing of the flat skins are also much less than those due to the shearing of the groove, and therefore negligible. In this equivalent model, the folded core sandwich is considered to be a homogeneous material subjected to a horizontal shear between the two faces, the horizontal shear modulus (equal to the transverse shear modulus) is defined as follows (Fig. 4):

$$G^*_{zx} = \frac{\sigma_{zx}}{\gamma_{zx}} = \frac{F/bL}{u/h} = \frac{F}{u}\frac{h}{bL} \tag{16}$$

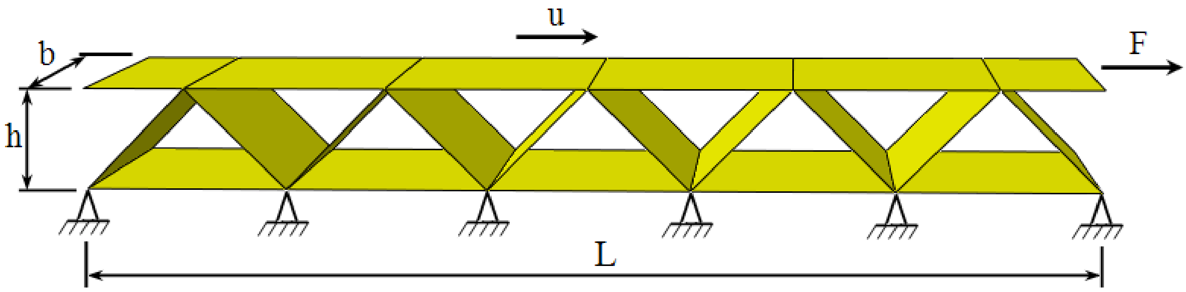

Fig. 4. The equivalent model to determine shear stiffness on MD section

The problem returns to determine the F/u ratio analytically or numerically. Thus, the stiffness of the transverse shear MD depends on the Young's modulus of the groove instead of their shear modulus, since the core layer behaves like thin walls in tension and compression, unlike the behavior of layers in laminate theory.

To determine the F/u ratio analytically, we consider a period length of the folded core sandwich as shown in Fig. 5. We fix the lower face and apply the force F on the upper face to give the sliding *x*. We divide the displacement *x* into two components *u* and *v*. These displacements can be determine as follows:

$$\begin{cases} u\cos\theta - v\sin\theta = \delta_1 = \dfrac{N_1 l}{E_{11}^b A} \\ u\sin\theta + v\cos\theta = \delta_2 = \dfrac{N_2 l}{E_{11}^b A} \end{cases} \tag{17}$$

with

$$N_1 = N_2 = N = \frac{F}{2\cos\theta};\quad l = \sqrt{h^2 + \frac{P^2}{4}};\quad \sin\theta = \frac{h}{l};\quad \cos\theta = \frac{P}{2l};\quad A = t^b.b$$

where *N* is the axial internal force in the core, *l* is the length of one-half period of core, *h* is the height of core, and *P* is the period of core, E_{11}^b is the Young's modulus of the folded core.

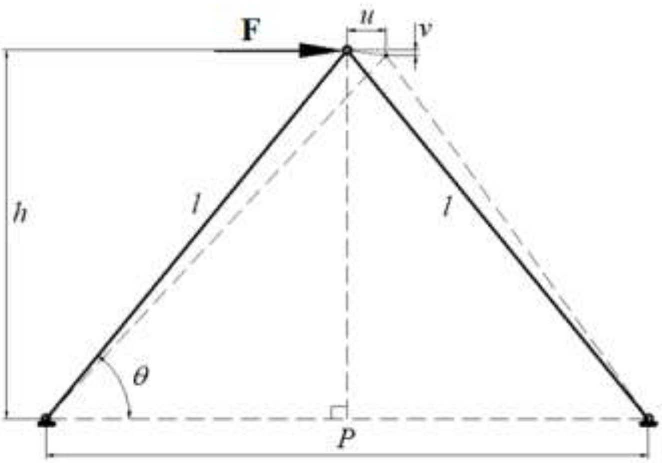

Fig. 5. The displacement model in a period of the core

It should be note that the *v* component is much less than *u* component, and therefore negligible. So, the *u* displacement can be determine by:

$$u = \frac{Fl(2h+P)}{2E_{11}AP} \tag{18}$$

Finally, the shear stiffness of the folded core sandwich on MD section is:

$$F_{11} = G_{zx}^*.h = \frac{2E_{11}^b t^b P.h^2}{l^2(2h+P)} \tag{19}$$

IV. VALIDATION OF HOMOGENIZATION MODEL

To validate our homogenization model (H-Model), a folded core sandwich panel with the dimension *L* = 160 mm and *B* = 150 mm is used. We first discretize the three layers of folded core plate by shell elements S4R of Abaqus to obtain the model Abaqus-3D. Then, we discretize the middle surface of folded core plate by shell elements S4R of Abaqus combined with our H-Model (using "user's subroutine UGENS") to obtain H-2D model. The comparison of the results allows us to evaluate the efficiency and accuracy of our homogenization model.

The calculations and comparisons are made on a folded core sandwich panel having CD section illustrated in Fig. 2, the geometrical parameters are: t^a = 0.2 mm, t^b = 0.15 mm, t^c = 0.2 mm, h = 4 mm and P = 8 mm. The properties of material are given in the Table 1. The rigidities of 2D equivalent plate are calculated as shown in Table 2.

Table 1. The material properties of three layers formed folded core plate

Layers	E_{11} (MPa)	E_{12} (MPa)	G_{12} (MPa)	ν_{12}
a	2372.6	704.2	493.1	0.377
b	1094.7	856.4	165.9	0.421
c	2372.6	704.2	493.1	0.377

Table 2. Rigidities of the 2D equivalent plate

Rigidities	A_{11} (N/mm)	A_{12} (N/mm)	A_{22} (N/mm)	D_{11} (N.mm)	D_{12} (N.mm)	D_{22} (N.mm)	F_{11} (N/mm)	F_{22} (N/mm)
Value	990.838	110.870	475.755	3966.656	443.851	1419.624	82.103	35.193

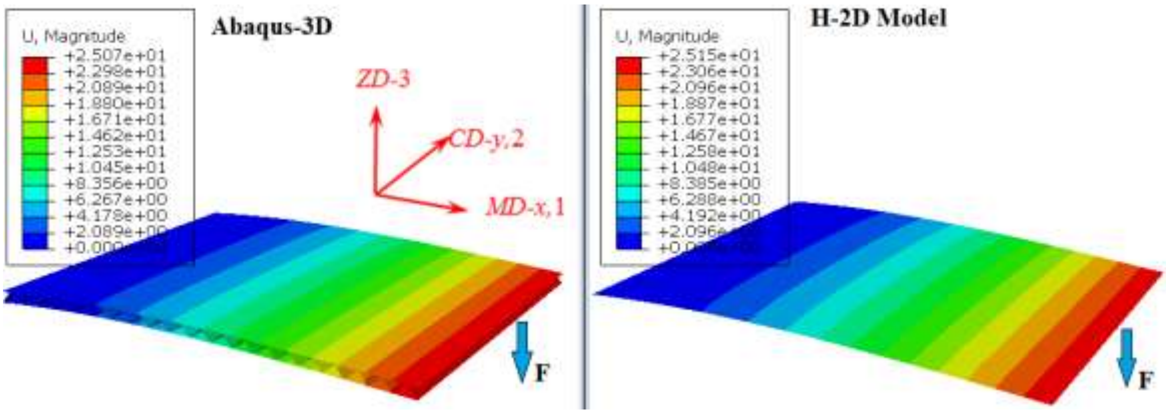

Fig.6 Simulation of Abaqus-3D and H-2D Model in shear force on MD section

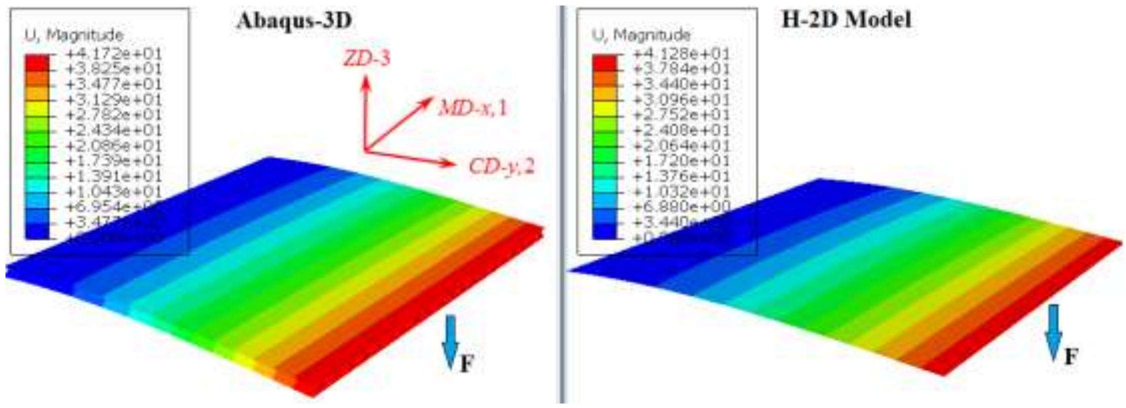

Fig. 7 Simulation of Abaqus-3D and H-2D Model in shear force on CD section

Table 3. Comparison between Abaqus-3D and H-2D model in bending

Vertical force F_3 = 10N		Abaqus-3D	H-2D Model	Error (%)
MD	Displacement U_3 (mm)	25.0683	25.1538	-0.36
	CPU time (s)	13	1.2	10.8 times
CD	Displacement U_3 (mm)	41.7148	41.2827	1.03
	CPU time (s)	12.2	1.1	11 times

We fix the plate at the left end and apply the vertical force (F = 10 N) at the right end. In both types of simulations (Abaqus-3D model and H-2D model), a rigid plate is bonded to the MD or CD section at the right end of the folded core sandwich panel to better apply forces. The deformed shapes together with the iso-values of displacement of the panel under transverse loading obtained by 3D shell Abaqus and our H-2D model simulations are shown in Fig. 6. and Fig. 7. The comparisons of results obtained by the two models and the percentages of error in H-2D model compared to Abaqus-3D results for the case of transverse loading are presented in Table 3. We observe that the calculations by our H-2D model are very fast while calculations by Abaqus-3D are much longer (11 times) and we note that the numerical results given by the two models are very close.

V. CONCLUSION

In this paper, we have proposed an analytic homogenization model for the bending and transverse shear problems of a sandwich panel with a folded core. The comparison of the results obtained by the Abaqus 3D and the Abaqus–Ugens H-2D simulations have proved the validation of the present homogenization model for bending and transverse shear problems. The present H-2D model allows us to largely reduce not only the time for the geometry creation and FEM calculation, but also the computational hardware requirements for the large sandwich panels. This homogenization model can be used not only for corrugated cardboard plates, but also for naval and aeronautic composite structures.

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