MULTI-OBJECTIVE OPTIMAL DESIGN OF ADHESIVELY BONDED CORRUGATED SANDWICH STRUCTURES UNDER THREE-POINT BENDING

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Abstract. This paper considers the optimisation design procedures in relation to various geometric parameters on adhesively-bonded corrugated sandwich structures when the adhesive joint failure effect was considered. This study presents four kinds of design parameters: core sheet thickness ($t_c$), face sheet thickness ($t_f$), core sheet height ($h_c$) and adhesive layer overlap width ($f$). Additionally, we conducted an experimental and numerical simulation on the three-point bending test of the longitudinal and transverse shape configurations. Force-displacements curves have been used to determine the deformation pattern and failure behaviour of the structure. The strength of the adhesive joint plays a vital role for the whole sandwich structure. To determine this, we used the cohesive zone method to obtain detailed stress distributions in the adhesive layer. For optimising a layout of the adhesively-bonded corrugated sandwich structures determined by the design parameters, we have proposed an integrated process established by multiple software platforms based on the Radial basis function methodology and multi-objective optimisation (NSGA-II). A design matrix with four factors and 120 designs was generated through the optimal Latin hypercube method. Force at adhesive failure, displacement at adhesive failure and weight were used to evaluate the strength performance of the adhesively-bonded corrugated sandwich structures. Finally, the obtained results show that adhesively-bonded corrugated sandwich structure at a longitudinal shape configuration have better performance.

Keywords: optimal design, corrugated sandwich structure, adhesive joint, radial basis function, three-point bending, adhesive failure

1. Introduction

Sandwich structures are attractive in multiple different branches of industry. They play a significant role due to their weight savings, fire resistance and enhanced thermal performance [1]. The main parts of any sandwich structure include the core and face sheets which require appropriate technical approach when joining them. One of the techniques of joining core and face sheets is adhesive bonding. In practice, adhesively-bonded corrugated sandwich structures (ABCSS) are efficient, and are made of a low-cost and lightweight material widely used for a variety of industrial needs [2]. A typical
ABCSS comprises a lightweight core sandwiched between two face sheets. When made of metallic materials (Fig. 1), the corrugated sheets are also attractive for industrial applications (e.g. airplanes, marine, railway and automotive vehicles). A variety of core geometries are available for corrugated sheets, including sinusoidal, triangular, trapezoidal and rectangular-shaped cores, bonded by either one or two face sheets [3].

To save on manufacturing costs in the case of corrugated structures and to avoid weight problems for structural sheets, it is important to design the sandwich panels with a minimum weight in mind, so that they are stiff and strong enough. Because of their importance, it has been recommended that more experiments on ABCSS should be undertaken to verify the optimum design characteristics of the detailed core sheet geometry, bond joints and face sheets. Despite the significant trends in analysing ABCSS by various researchers, there are still knowledge gaps. For example, the reviewed studies do not consider the adhesively-bonded joint strength of the corrugated sandwich structures which are determined by adhesive properties, bonding strength, adherents and their interfaces. The objectives of this study were: 1) to provide detailed optimised results of ABCSS which consider their interfaces’ strength behaviour and 2) to analyse the design optimisation of corrugated sandwich structures in order to reduce their deformation displacements parameters with lightweight and strength design properties. In this paper, the minimum weight, displacement (buckling, indentation) and strength of a corrugated structure was analysed when the structure was subjected to a three-point bending load. The three-point bending load optimisation was calculated using an optimisation procedure based on the Optimal Latin hypercube (OLH) method. Optimising the displacement parameter helps to reduce the effect of the buckling and indentation of ABCSS. The accuracy of the fitting models was verified by error statistical analysis. Additionally, the key point of the optimisation research was the failure result (damage initiation zone, etc.) that appeared in the adhesive layer under three-point loading. The generated results will provide an insight into the design of ABCSS that is appropriate for industrial needs.

2. Materials and methods

2.1 Experimental materials

Hot stamping 22MnB5 steel for the core sheet and high strength boron steel 301 for the face sheets were selected as the adherents for ABCSS. The mechanical properties of the adherents are shown in Table 1 based on the manufacturer’s data. In the current study, the ductile structural adhesive DOW Betamate 1840C was investigated, and, after curing for 24h, the specimens were allowed to cool in air before we reassembled the de-clamping device. The collected adhesive mechanical properties and the curing conditions from the manufacturers have been given in Table 2.

<table>
<thead>
<tr>
<th>Property</th>
<th>High strength boron steel 301</th>
<th>Ultra-high strength steel 22MnB5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, $E$ (GPa)</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td>Poisson’s ratio, $v$</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Tensile yield Stress, $\sigma_y$ (MPa)</td>
<td>310</td>
<td>1000</td>
</tr>
<tr>
<td>Tensile failed Stress, $\sigma_f$ (MPa)</td>
<td>500</td>
<td>1750</td>
</tr>
</tbody>
</table>
Table 2- Mechanical properties and curing condition of the adhesive
Таблица 2- Механические свойства и условия отверждения клея

<table>
<thead>
<tr>
<th>Property</th>
<th>DOW Betamate 1840C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, $E_a$ (GPa)</td>
<td>2.74</td>
</tr>
<tr>
<td>Tensile stress, $T_I$ (MPa)</td>
<td>27.5</td>
</tr>
<tr>
<td>Tensile failure strain, $\varepsilon_I$ (%)</td>
<td>1.1</td>
</tr>
<tr>
<td>Shear modulus, $G_a$ (GPa)</td>
<td>0.17</td>
</tr>
<tr>
<td>Shear stress, $T_{II}$ (MPa)</td>
<td>28.7</td>
</tr>
<tr>
<td>Shear failure strain, $\varepsilon_{II}$ (%)</td>
<td>27</td>
</tr>
<tr>
<td>Curing temperature/time ($^\circ$C/min)</td>
<td>180/120</td>
</tr>
</tbody>
</table>

2.1.1 The three-point bending experimental test

Two types of corrugated shape configurations with longitudinal and transverse sections were considered. The three-point bending (3PB) test for ABCSS was considered for four specimens for each condition (Fig.2). The geometrical parameters of the specimens are $t_f=2.5$ mm, $h_c=18$ mm, $t_c=1.5$ mm, $t_a=0.2$ mm, $f=8$ mm, $p=25$ mm, $\theta=57.5^\circ$, $r=10$ mm. The ABCSS specimens were 50 mm wide and 200 mm long. The device shown in Fig. 3 was designed and built for the 3PB test procedure and based on the standard ASTM D7766 [4]. In all cases, the support positions were fixed at the corrugation crown bonded areas. The ABCSS specimens were analysed in transverse and longitudinal configurations tests. The ABCSS specimens were tested in 3PB test, i.e., the ABCSS specimens were simply placed on two round blocks and the indenter was applied at the mid-point between the supports by a cylinder oriented across the specimen. The diameter of the indenter’s head and support blocks was Ø30 mm. The velocity of the indenter was 5mm/min. All of the experiments were conducted in an environment with $20^\circ$C and 50% relative humidity.
2.1.2 Numerical modelling

ABCSS was analysed using the explicit FE software Abaqus®, which was subsequently used to construct the triangular cohesive law [5]. The traction-separation cohesive zone model (CZM) law was used for simulating the mechanical behaviour of the adhesive layer and the power-law was applied to simulate the adhesive layer damage evolution process [6]. The adhesive layer between the face and core sheets was assumed to be perfect. The indenter and support blocks were designed as rigid bodies. The ABCSS was simply held together by supporters similar to real experiments (Fig.3,4). A four-node cohesive mesh element COH3D8 was used for the adhesive layer. Generally, the accuracy of FEA increases with the increase of the element number. However, computing expenses should also be considered, especially as the mesh size of the adhesive layer joints particle (cell) was 0.5x0.5x1.6 mm. The 3D linear hexahedral elements C3D8R was applied for the core and the face sheets. The interactions between the support blocks, face sheets and core sheets was modelled using surface-to-surface contacts under the “Hard” contact. A frictional

coefficient value of 0.35 was assumed among all contacting surfaces. The displacement parameter was measured until damage initiation zone failure appeared in the adhesive layer. The failure in the adhesive layer was controlled and measured by Scalar stiffness degradation (SDEG). All of the stresses were obtained from the Report field output. Local adaptive meshing strategy was used to re-mesh the adhesive connections with the objective of reducing the error in the bonded areas [5].

Damage initiation in the adhesive layer can be specified through different criteria and in this study, a maximum nominal stress criterion was in place with an assumption that damage was initiated when either the peel or shear traction ($t_I$ or $t_{II}$) exceeded the tripping traction ($T_I$ or $T_{II}$), as shown in the equation below [6,7]:

$$\max\left\{ \frac{(t_I)}{T_I}, \frac{(t_{II})}{T_{II}} \right\} = 1$$

(1)

where $\langle \rangle$ is the Macaulay bracket constraint, implying that a compression stress state does not lead to damage initiation.
2.2 Optimisation method

Longitudinal and transverse - two types of shape configurations of ABCSS - were designed for the optimisation criteria under three-point loading as illustrated in Fig.2. Before the model verification, three evaluation indicators were defined. They include the minimum weight and displacement (buckling). Finally, the strength of ABCSS was analysed. It begins with a stress analysis of the core and the face sheets coupled with failure analysis based on yielding, buckling and adhesive damage initiation which was controlled and accepted by numerical simulation. Adhesive joint failure is the key point which would lead to the destruction of the whole ABCSS. All of the collected failure data was obtained from FEM and integrated by iSight® to execute the OLH (optimal Latin hypercube) experimental design and to obtain the response surface models. Taking into account the weight, displacement and strength as the optimisation objectives, NSGA-II (Non-dominated Sorting Genetic Algorithm), a multi-objective optimisation method was utilised to find the Pareto-optimal frontier which reveals the optimal parameters of ABCSS.

In this study, design of experiment (DOE) was used to reveal the relationship of the design parameters and responses using a necessary number of sample points [8]. To overcome the design parameters of ABCSS, one can use the OLH method. OLH is a method of DOE in which the number of levels of each factor is equal to the number of design points evenly spread within an n-dimensional space defined by n factors through a combination of optimisation. Table 3 shows the geometrical range of the ABCSS parameters. A design matrix with four factors design parameters and 60 levels for each shape configuration is displayed in Table 3.
The workflow of optimization design process has been shown in Fig.5.

Table 3 - The geometrical range of ABCSS parameters

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Lower value</th>
<th>Upper value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face sheet thickness, $t_f$</td>
<td>0.2</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Core sheet thickness, $t_c$</td>
<td>0.2</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Adhesion overlap width, $f$</td>
<td>3</td>
<td>12</td>
<td>mm</td>
</tr>
<tr>
<td>The height of core sheet, $h_c$</td>
<td>3</td>
<td>10</td>
<td>mm</td>
</tr>
</tbody>
</table>

*Adhesive layer thickness is $t_a$=0.2mm.

2.2.1 Radial Basis Function model establishment

In this paper, we performed the optimal design of ABCSS using the approximation technique of Radial Basis Function (RBF) method in iSight®. RBF network is a neural network algorithm with simple architecture, simple training process and widespread application [9]. RBF is a feed-forward network with a single hidden layer, and has some advantages that can approximate any continuous function with arbitrary precision. RBF uses an adaptive structure, in which the output values are unrelated to the initial values, and so on. RBF neural network has been widely applied in dealing with some traditional classification problems [10]. Radial basis function models use linear combinations of radially symmetric functions to interpolate sample data points. The simplest form of these models is:

$$\hat{y}(x) = \beta_0 + \sum_{i=1}^{N} \beta_i \|x - x_i\|$$  \hspace{1cm} (2)

where, $\|\cdot\|$ is the Euclidean distance, $N$ is the total number of sample points, $x_i$ is the $i$-th sample point, and the $\beta$'s are model parameters found by solving a linear system of $N$ equations.

The optimised approximation models results from the RBF module were used to find the optimal values of three design variables through 60 simulations for each configuration.

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Fig.5- The flowchart of the ABCSS optimization design process

Рис.5 - Блок-схема процесса проектирования оптимизации ABCSS
2.2.2 NSGA-II optimization method

Non-dominated Sorting Genetic Algorithm (NSGA-II) is a popular non-domination-based genetic algorithm for multi-objective optimisation. It is a very effective algorithm [10] which has a better sorting ability. In this paper, a modified version of NSGA-II was implemented to solve the proposed multi-objective optimisation design of ABCSS. In the NSGA-II, each objective parameter was treated separately. The standard genetic operation of mutation and crossover were performed on the designs. The selection process was based on two main mechanisms; "non-dominated sorting" and "crowding distance sorting". By the end of the optimisation run, a Pareto set was constructed where each design had the "best" combination of objective values and improving one objective was impossible without sacrificing one or more of the other objectives [11]. The iSight® implementation of NSGA-II was used to calibrate the model on the applied case study (Fig.5). Objective functions were considered as all of the error measures were also considered.

Force, Weight and Displacement are three conflicting responses. When Force attains the minimum value, Weight and Displacement uniformity is less obvious, and vice versa. Therefore, the multi-objective optimisation method, which was used to compromise the three objectives, was utilised to explore the optimal layout of ABCSS. The mathematical description of the optimisation problem is given as:

\[
\begin{align*}
\text{Minimise:} & \quad \text{Weight (W)}, \\
\text{Minimise:} & \quad \text{Displacement (D)}, \\
\text{Maximise:} & \quad \text{Force (F)}. \\
\text{Parameter range:} & \quad \{h_c, f, t_c, t_f\} \text{ abide by Table (4).}
\end{align*}
\]

s.t. \(3\text{mm} \leq h_c \leq 10\text{mm}; 3\text{mm} \leq f \leq 12\text{mm}; 0.2\text{mm} \leq t_c \leq 1\text{mm}; 0.2\text{mm} \leq t_f \leq 1\text{mm}\)  \(3\)

3. Optimisation results

The longitudinal and transverse shape configuration analyses are two types of shape configuration designed for strength and weight criteria and minimising their deformation displacements under 3PB loading condition. In the strength (i.e., load-displacement) design of two shape configurations, the geometrical size of the ABCSS was optimised in consideration with adhesive joint thickness of \(t_a=0.2\text{mm}\). By using the optimisation method, each objective was treated separately.

The sample points in the design matrix were executed automatically by an integration flow established by iSight® software which transferred the data information between the ABAQUS® and data component. iSight® provides various components to help study or improve the DOE. The parameterised CAD model was created by CATIA®, and then the CAD routine was mapped to ABAQUS®. Next, the process data of the longitudinal and transverse shape configurations were simulated by ABAQUS® and extracted to perform the data process. According to the design matrix, including four design parameters and 60 samples for each shape configuration, the workflow auto-ran 120 times in total. These samples were used to determine the radial basis function model to describe the characterisation of the mathematical relationship between the design parameters and responses. It was noted that Force or “Force at failure” (\(F\)) or Displacement or “Displacement at failure” (\(D\)) and Weight (\(W\)) varied for the different designs. The adjusted \(R^2\) square coefficients of Weight, Displacement and Force were 0.9 respectively.

For the ABCSS at the longitudinal direction, the core thicknesses and height of the core effects Force and Weight. However, face thickness does not greatly affect Displacement. To prevent the face buckling under three-point bending load, the core was made stiff and strong enough to retain the face sheets from buckling. For Displacement, core thickness shows a big influence. The overlap
adhesive overlap width $f$ shows a positive influence on the Displacement parameter. The adhesive overlap width (flange) shows good structural efficiency and high stiffness. This study also shows that overlap width (flange) size and core sheet thickness were relatively weak variables in the sandwich design for high efficiency. Finally, it was demonstrated that the core height and web angle had the greatest influence on the efficiency of ABCSS, whereas the overlap width (flange) and core thickness were the weaker parts in the performance of ABCSS [1].

For ABCSS at the transverse configuration, the face thicknesses play an important role on the Force and Weight parameters. Increasing the overlap adhesive width $f$ shows a good influence on Force because the core sheet flange support needs more support area. Several parameters such as face thickness, core height and overlap adhesive width show a big influence towards Displacement. The most important parameter for Force parameter is face thickness, because the face sheets work for tension and compression at the same time and increase the strength of ABCSS. Core sheet height, overlap adhesive width and face thickness play a main role in Displacement. Nevertheless, the adhesively bonded area could be further optimised to maximise strength and stiffness of ABCSS [1].

By using the multi-objective optimisation algorithm, the Pareto front of the optimisation problem was defined in Eq.(3) and was obtained as shown in (Fig.6). The designers can then select the optimal point according to their emphasis on these two types of ABCSS.

Fig.6 - 3D-figure for optimal Pareto set of multi-objective optimization:

b) Рис.6 - 3D-фигура для оптимального набора многоосевой оптимизации Парето:
c) a) продольное; б) поперечный

4. Conclusions

The ABCSS with longitudinal and transverse shape configurations were optimised and comparatively studied in explicit FEM, while OLH, radial basis function and NSGA-II method were utilised during the three-point bending design procedure. The experimental results were also used to validate the simulation results. Based on the models, stress with critical load in each member of ABCSS can be predicted and the failure in the adhesive layer has been identified as a key parameter of the whole structure.

For the longitudinal shape configuration, it was found from the optimisation procedure that Force increased as the wall core thickness $t_c$ increased. Increasing the adhesive overlap width $f$ showed a great influence towards the whole structure of ABCSS that led to the increase of Force. When we increased the height of the core, $h_c$, Displacement increased accordingly. The face thickness directly influenced Weight and
Displacement. When the core thickness and height of the core were kept constant, the core cell shape had a relatively big effect on the longitudinal shape responses.

The transverse shape configuration totally depended on the face sheet thickness, $t_f$ and overlap adhesive width, $f$. The overlap adhesive width $f$ had a great effect on stress distributed in the adhesive layer for both shape configurations. It is more important to the whole ABCSS compared with other failure modes. The face sheets carried the acting stress and worked at tension-compression stresses for the upper and bottom face sheets. A comparison of two types of configuration of ABCSS found that the bending strength of the longitudinal was better than the transverse ones under the 3PB loading condition. Finally, a multi-objective optimisation was performed by iSight, which is a powerful tool which provides engineers with a broad design ranges to help them in making their final verdict.

REFERENCES

склеенных корректированной сэндвич-конструкций, предложен комплексный процесс, установленный несколькими программными платформами на основе радиальной базисной функции (Radial basis function) и не доминирующий генетический алгоритм сортировки (NSGA-II). Нагрузка (до разрушения клея), вдавливание и вес были использованы для оценки прочности показателей адгезивно-склеенных сэндвич-панелей. Наконец, полученные результаты показывают, что адгезивно-склеенные корректированные сэндвич-панели при продольной конфигурации имеют более высокую прочность.

Ключевые слова: оптимальный дизайн, сэндвич панель, клееное соединение, трехточечный изгиб, дефект клея.

ЖЕЛИМДЕЛГЕН СЭНДВИЧ-КУРЫЛЫМЫНЫҢ КӨПКРИТЕРАЛДЫ УШ НҮКТЕЛІ ИІЛУ КЕЗІНДЕГІ ОПТИМИЗАЦИЯЛАУ

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Андатпа. Адгезивті-жабыстырылған корректировленген сэндвич панелдерінің геометриялық параметрлер бойынша оптимизациялау процесси карастырылған. Торт параметрлері зерттелген: сыртқы панель қалыңдығы, ортаңғы корректировленген панель қалыңдығы, корректировленген панель биіктігі мен желім қосынысының ұзындығы. Сонымен қатар, эксперименттік жəне компьютерлік модельдеу шаралары жасалған. Адгезивті жабықтан жерлери оте манызды қызмет аткаргандақтан, осыған ерекше назар аударылған. Осыған қосынысы жəңе қосынысының ұзындығы. Оптимизация процесстерінің келесі тəсілдері колданылған. Беріктілік (желім істен шыққанша), панельдің майсысы жəңе оның салмағы бағаланып, оптимизацияланып, қосынысының ұзындығы. Оптимизация процесстерінің тəсілдері колданылған Radial basis function жəңе NSGA-II. Алынған нәтижелер көрсеткен, адгезивті-жабыстырылған корректировленген сэндвич панелдерінің ішінде бойлық конфигурациясы жоғары сенімділік көрсетті.

Түйінді сөздер: оптимальды дизайн, сэндвич панелі, желімді қосылық, уш нүктелі майыстыру, желім сынуы

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