Experimental study of partially-cured Z-pins reinforced foam core composites: K-Cor sandwich structures

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Abstract This paper presents an experimental study of a novel K-Cor sandwich structure reinforced with partially-cured Z-pins. The influence of pultrusion processing parameters on Z-pins characteristics was studied and the effect of Z-pins on mechanical properties was disclosed. Differential scanning calorimetry (DSC) and optical microscopy (OM) methods were employed to determine the curing degree of as-prepared Z-pins and observe the implanted Z-pins in the K-Cor structure. These partially-cured Z-pins were treated with a stronger bonding link between face sheets and the foam core by means of a hot-press process, thereby decreasing burrs and cracking defects when the Z-pins were implanted into the Rohacell foam core. The results of the out-of-plane tensile tests and the climbing drum peel (CDP) tests showed that K-Cor structures exhibited superior mechanical performance as compared to X-Cor and blank foam core. The observed results of failure modes revealed that an effective bonding link between the foam core and face sheets that was provided from partially-cured Z-pins contributed to the enhanced mechanical performances of K-Cor sandwich structures.

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1. Introduction

In order to satisfy the ever-increasing demands of light weight, high specific strength, and durable stability for structural components used in aircraft flap, a plane’s tail and wings, etc., sandwich structures reinforced with Z-pins have been considered as one of the most promising candidates because of their low density, high design-ability, and excellent mechanical properties. Since an X-Cor sandwich structure was designed by AZTEXTM in the United States in 1978, several studies of the mechanical properties of X-Cor structures have been investigated during the past decades.1-6

For X-Cor, the uncured face sheets are pressed on each side of the foam core to support the Z-pins. During the process of curing treatment, the highly-cured Z-pins will damage the face sheets into which they are implanted, eventually resulting in weak performance along “Z-direction” (i.e., perpendicular to the panel). The above shortages have restricted further applications of X-Cor structures, especially when they are operated under large loading forces of bending deformation, tensile or shear strain.7,8

Based on the traditional X-Cor (see Fig. 1(a), a novel K-Cor sandwich structure (see Fig. 1(b) was developed by AZTEXTM in 2005.7 In the case of the K-Cor structure, the
required Z-pins are partially cured, and the extend parts are folded back and bonded onto the foam surface by a hot-curing process. In recent years, this novel structure has attracted many research interests due to its super mechanical performances (e.g., high strength, low density, and structural stability). For instance, Casari et al.\textsuperscript{10} studied the typical characteristics of K-Cor structures. The mechanical properties of X- and K-Cor structures were compared by Andrea et al.\textsuperscript{11} which involved plane tension, shear, and compression tests. Furthermore, Zheng et al.\textsuperscript{12} presented the dynamically mechanical models for K-Cor structures based on compression and tension tests.

According to the literature review, it revealed that very few research studies focused on the mechanical properties of the K-Cor structure. Especially, there was no comprehensive investigation on partially-cured Z-pins used in the sandwich structures. Hence, the objectives of this paper were to study K-Cor structures reinforced with partially-cured Z-pins, and to evaluate their mechanical performances using the out-of-plane tension and CDP tests. As significantly improved tensile and peeling strengths are obtained, the novel K-Cor structure can be employed as a structural component applied in the field of spacecraft and aerospace engineering.

2. Experimental procedures

2.1. Raw materials

Rohacell-31 WF foam was used as the foam core with a thickness of 12.1 mm. The unidirectional prepreg US12500 as [0/90]/C\textsubscript{176} was served as the face sheets and stacked in a quasi-isotropic ply pattern with a nominal thickness of 1 mm. The required Z-pins with a diameter of 0.5 mm were made by T300/epoxy and used as the reinforcing bars to be implanted into the foam.

2.2. Curing degree of Z-pins

Processing parameters of pultrusion for preparing Z-pins were determined in our previous study.\textsuperscript{12} As experimental results were obtained, low-cured Z-pins were too soft to be easily implanted into the foam; whereas the Z-pins with a higher curing degree were too hard to be well pressed into the foam surface. In order to prepare the appropriate curing degree of Z-pins used in the K-Cor structures, the DSC technique was employed to estimate the curing degree of Z-pins. As observed from the DSC scans shown in Fig. 2, the exothermic peak of T300/epoxy resin was from 90 °C to 160 °C. The mold temperature was thus selected at 90 °C to make the full thermal reactions. Hence, the oven temperature was selected as 130, 135, or 140 °C to make a comparison. The speed of pultrusion was set at 3.24 mm/s. In addition, a similar exothermic peak of the face sheets was recorded from the DSC scans, revealing that the cross-linking reaction occurred at the interface between face sheets and Z-pins.

To estimate the curing degree of the as-prepared Z-pins, the thermodynamic formulas are given by

\[ \Delta H = \int_{t_1}^{t_2} \Delta P \, dt \]  
\[ \xi = \frac{\Delta H_{t_2}}{\Delta H_{t_1}} \times 100\% \]  

where \( \Delta H \) is the enthalpy of the fiber from the DSC scans; \( \Delta P \) is the average value of power input; \( t_1 \) and \( t_2 \) are the initial and terminal temperatures of exothermic peaks; \( \xi \) is the curing degree of Z-pins; \( \Delta H_{t_1} \) and \( \Delta H_{t_2} \) present the totally exothermic enthalpy extending from \( t_1 \) to \( t_2 \).

According to the measured results listed in Table 1, the lowest curing degree of Z-pins prepared at 90 °C/130 °C/3.24 mm/s was 41.55%, while these Z-pins were too soft to be easily implanted into the foam. In addition, two typical Z-pins at 90 °C/135 °C/3.24 mm/s (45.59%) and 90 °C/140 °C/3.24 mm/s (61.22%) were well implanted into the foam and pressed flat on the foam surface by a hot-press process.

To better illustrate the inner 3D structure of Z-pins used in K-Cor, the foam core was dissolved using a 30 wt.% NaOH solution at 50 °C (as seen in the top-right corner of Fig. 3a),\textsuperscript{13} with the experimental results displayed in Fig. 3(a) and (b).

![Fig. 1 Schematic diagrams of two typical sandwich structures.](image1)

![Fig. 2 DSC curves of T300/epoxy resin and face sheets at a heating rate of 5 °C/min.](image2)

<table>
<thead>
<tr>
<th>Mold temperature (°C)</th>
<th>Oven temperature (°C)</th>
<th>Pultrusion speed (mm/s)</th>
<th>( \xi ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>130</td>
<td>3.24</td>
<td>41.55</td>
</tr>
<tr>
<td></td>
<td>135</td>
<td>3.24</td>
<td>45.59</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>3.24</td>
<td>61.22</td>
</tr>
</tbody>
</table>
The Z-pins were removed from the structure and examined whether they were damaged using an optical microscope (OM). As revealed from magnified micrographs of destroyed structures, the Z-pins with a curing degree of 61.22% were seriously cracked at the bending area, resulting in poor bonding strength. For comparison, Fig. 3(b) shows the undamaged Z-pins (45.59%) used in K-Cor, revealing the partially-cured Z-pins could be well bent onto the foam surface without any brittle failure.

2.3. Fabrication of K-Cor sandwich structures

In this study, Z-pins acted as the reinforcing bars and were implanted into Rohacell-31 WF foam by an implanter at an angle of 70°. The as-prepared Z-pins with a uniform density of 7 mm x 7 mm were implanted into the foam, and the free length of Z-pins outside the foam core was 5 mm, as illustrated in Fig. 4.

Detailed procedures for fabricating K-Cor structures were presented in Fig. 5. Firstly, partially-cured Z-pins were implanted into the foam core. The outside portions of Z-pins were then pressed flat on the surface of the foam core by a hot-press process. The face sheets were adhesively bonded onto the foam core. The sandwich structure was finally cured in an autoclave at 130 °C under a pressure of 0.2 MPa for 2 hours.

3. Results and discussion

3.1. Mechanical properties of Z-pins

The mechanical properties of partially-cured Z-pins were determined using tensile tests according to the GB/T 3362-82 (standard test method for tensile properties of carbon fiber strands), as shown in Fig. 6(a) and (b). The strength and ductility of the as-prepared Z-pins can be determined by:

\[ \sigma = \frac{P}{A} = \frac{4P}{\pi D^2} \]  

\[ \varepsilon = \frac{\Delta L}{L} \times 100\% \]
where $\sigma$ and $\varepsilon$ represent the average values of tensile strength and elongation rate for the as-prepared Z-pins, $P$ is the applied load, $A$ is cross-sectional area, $D$ is the diameter of the investigated Z-pins (0.5 mm), $L$ is the original length of measured Z-pins (200 mm), and $\Delta L$ is the extended length of Z-pins after tensile tests.

All of the tensile tests were repeated three times in order to confirm the reproducibility of experimental results. The average values of tensile strength ($\sigma$) and elongation rate ($\varepsilon$) were 68.75 MPa and 0.25%, thereby revealing the excellent mechanical properties of Z-pins used in the K-Cor structure.

### 3.2. Out-of-plane tension tests

To evaluate the effect of Z-pins on the tensile strength for K-Cor structures, out-of-plane tension tests were carried out according to the GB/T 1452-2005 (standard test method for plane tensile tests of unidirectional fiber reinforced plastics). Investigated specimens were cut into 60 mm $\times$ 60 mm by a grinding machine. As noted from Fig. 7, the applied stress increases with increasing strain, and then trends to the yielding stage until dropping down.

As observed from the failure modes in Fig. 8, cracking failures of X- and K-Cor structures were both initiated from the middle of the foam, and then the neighboring cracks propagated leading into the fracture of structures. While for the case of blank foam core without Z-pins attached, de-bonding cracks firstly occurred along the bonding interface between the foam and face sheets due to its poor internal bonding strength on “Z-direction”. It can reveal that reinforcing bars of Z-pins have improved the bonding strength of sandwich structures.\(^\text{(14)}\)

The tensile strength and modulus of investigated specimens are calculated by

$$
\sigma = \frac{P_{\text{max}}}{A}
$$

$$
E_c = \frac{\Delta P h}{\Delta h A}
$$

where $\sigma$ is the tension strength; $P_{\text{max}}$ is the loading force; $E_c$ is the tensile modulus; the value of $\Delta P$ represents the load increment of line segment in the tensile curves; $\Delta h$ is the incremental displacement corresponding to $\Delta P$; the value of $h$ is the nominal thickness of measured samples (10 mm).

The results of tensile strength and their modulus are listed in Table 2. The mechanical properties of K-Cor are much higher than those of X-Cor and blank foam core. High curing degree of Z-pins used in X-Cor results in poor bonding strength because of the insufficient mechanical link between the face sheets and the foam core. Whereas for K-Cor, the length of partially-cured Z-pins beyond the foam core is more than 5 times longer than that for X-Cor. Under the action of a hot-press process, partially-cured Z-pins can completely get cured with face sheets through the cross linking reaction.

![Experimental set-up of the tensile tests for Z-pins](image1)

![Typical stress vs. strain curve measured for Z-pins](image2)

![Failure modes of investigated specimens after tensile tests.](image3)
3.3. Climbing drum peel tests

The CDP tests were proposed to study the bonding strength between the face sheets and the foam core, which were performed on an SANS universal testing machine using a load range of 5 kN and a test speed of 20 mm/min. The tests were conducted according to the GB/T 1457-2005 (standard test method for climbing drum peel strength of sandwich constructions). The detailed shape of measured specimens and their parameters are shown in Fig. 9.

The applied load vs. displacement curves of CDP tests recorded for X-/K-Cor structures and blank foam core have shown an expected increase in the displacement with increasing applied load followed by a plateau in the applied load (as seen in Fig. 10). The presence of ‘stick-slip’ behavior in these curves is resulted from the Z-pins that acted as the rows of pinning cells. In this figure, each measurement contains two curves. The top one is the total load to roll up the face sheet with the drum plus the extra load that was used to peel the face sheet off from the foam core; while the bottom one represents the applied load to overcome the drum rolling up face sheets with no core attached. As revealed from Fig. 10d, the peeling strength of X-Cor is slightly higher than that of blank foam core, but much lower than that of K-Cor, which is mainly attributed to the Z-pins that acted as the reinforcing bars used in the sandwich structures. The area under the curves (energy put into peeling) can be estimated by

\[
M = \frac{(D - d)}{2b} \int_{P_0}^{P_b} dP = \frac{(P_b - P_0) \cdot (D - d)}{2b} \tag{7}
\]

where \(M\) is the peeling strength; \(P_0\) and \(P_b\) represent the applied load to overcome the drum rolling up face sheets without or with the foam core attached; \(D\) is the diameter of the roller.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\sigma_t) (MPa)</th>
<th>(E_c) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank foam core</td>
<td>1.12</td>
<td>41.39</td>
</tr>
<tr>
<td>X-Cor</td>
<td>1.28</td>
<td>50.85</td>
</tr>
<tr>
<td>K-Cor</td>
<td>1.45</td>
<td>63.52</td>
</tr>
</tbody>
</table>

Table 2 Results of the out-of-plane tensile tests.
flange; \(d\) is the diameter of the roller; \(b\) is the width of the tested samples.

As illustrated from the cracking modes in Fig. 11, a majority of the Z-pins used in the X-Cor were pulled out and de-bonded away from the interface between the foam core and face sheets. Owing to the full cross-linking reaction that occurred in the K-Cor, some of the partially-cured Z-pins were only broken at the bending place, hence leading to a high peeling strength. While for the blank foam core, the face sheet was de-bonded away from the foam core due to its poor bonding strength on “Z-direction”.  

To our knowledge, the mechanical properties of a sandwich structure are mainly dependent upon its bonding link that is induced by the reinforced Z-pins.  

As observed from optical photographs of face sheets in Fig. 12, completely-cured Z-pins of X-Cor are very hard so that they tend to damage the surface of face sheets. The ends of Z-pins beyond the face sheet are inserted into the face sheet resulting in decreasing the bonding strength. As for K-Cor, the partially-cured Z-pins are well bent onto the foam core, favoring the formation of a smooth surface. The undamaged surface has decreased the trend of bonding failure that is beneficial to improve the bonding link between the face sheets and the foam core. Moreover, the length of the completely-cured Z-pins outside the foam in X-Cor is only 1 mm, hence resulting in the point contact and a limited mechanical bonding. While for the case of K-Cor, the partially-cured Z-pins with a 5 mm length beyond the foam core can promote full cross-linking reactions with the face sheets, leading to the linear bonding link in replacement of point joint or slight mechanical bonding of X-Cor. It is thus predicted that an effective bonding link produced from partially-cured Z-pins contributes to the improved peeling strength of the K-Cor structure.

4. Conclusions

(1) The processing parameters of pultrusion on the Z-pins characteristic have been optimized using the DSC scans. The results indicated that the curing degree of T300/epoxy Z-pins processed at 90 °C (mold temperature), 135 °C (oven temperature), and 3.24 mm/s (pultrusion speed) was 45.59%. The average tensile strength and elongation rate of as-prepared Z-pins were 68.75 MPa and 0.25%.

(2) The observed results of the out-of-plane tensile tests have revealed higher tension strength and modulus as compared to X-Cor and blank foam core.

(3) Based on the results of the CDP tests, the peeling strength of K-Cor structures was 75.32 N that was much higher than those of X-Cor (37.13 N) and blank foam core (27.35 N). The improved peeling strength of K-Cor was attributed to the linear bonding link between...
the foam core and the face sheets that was provided from partially-cured Z-pins through the cross-linking reactions.

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References


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