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Structural Assessment and Repair Feasibility of Surface Defects in Composite Sandwich Panels

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Abstract. Composite sandwich panels are extensively used in aerospace, automotive, and construction applications due to their exceptional strength-to-weight ratio and structural efficiency. However, local surface deviations, such as waviness and dents, often develop during manufacturing and operation, potentially leading to adhesion failures and delamination between the composite skin and the core. This study aims to establish acceptable defect size limits that can be corrected through technological pressing, ensuring structural integrity of composite material while minimizing the negative impact on load-bearing capacity of sandwich panels. An analytical approach was adopted to assess the stress behavior of composite skins with waviness and elliptical dent defects. The analysis was based on beam and plate theory, incorporating the effects of flexural rigidity, material anisotropy, and applied technological pressure. The Hill strength criterion was applied to define permissible defect limits, considering variations in structural criticality levels. The study determined the maximum allowable sizes for waviness and dents in composite sandwich panels, factoring in the responsibility level of the panel, expressed as the maximum stress intensity coefficient. The results show that the acceptable defect size decreases with increasing structural criticality. It was also found that forced compression of dents induces pre-stress zones within the composite skin, potentially altering its stress distribution and reducing its long-term load-bearing capacity. The proposed methodology provides a quantitative framework for evaluating acceptable defect limits, supporting manufacturing quality control and repair optimization. The results offer practical insights for enhancing the reliability and durability of composite structures, ensuring that local surface deviations remain within permissible limits without compromising structural performance.

Introduction

Modern sandwich structures are widely used in the aviation, automotive, railway, and construction industries due to their high strength, low weight, and resistance to external impacts [1, 2]. The load-bearing skins of such structures are predominantly manufactured from polymer composite materials (PCM), which exhibit excellent mechanical properties, high corrosion resistance, and the ability to withstand substantial operational loads [3, 4, 5]. However, during manufacturing and service, polymer composite skins are prone to technological defects such as waviness, bulges, and dents [6, 7]. These imperfections often serve as precursors to insufficient adhesion zones, ultimately leading to delamination between the composite skins and the core of sandwich structures [8, 9]. Such defects significantly reduce the load-bearing capacity of sandwich structures, acting as stress concentrators that may cause premature failure of structural elements [10, 11].

Although these defects can be mitigated through technological interventions during the assembly of sandwich structures, the corrective processes inevitably induce residual stresses in the affected areas, which adversely impact the mechanical performance of the component [12, 13]. This underscores the necessity of a comprehensive approach to investigating surface defects in sandwich panels, assessing their influence on structural integrity, and developing methods to minimize their detrimental effects.

Literature Review

Recent research on sandwich composite panels has extensively examined various aspects of their mechanical behaviour, including delamination propagation, buckling, residual strength after damage, and the impact of defects on structural performance. The study in [14] introduces an analytical approach for predicting delamination propagation due to buckling in composite load-bearing skins. A parametric investigation evaluates how delamination geometry affects the structural behaviour of different PCM. While this research provides valuable insight into delamination growth, its primary focus remains on global stability, with limited consideration of localized manufacturing deviations such as dents and waviness in sandwich panels. Furthermore, the proposed model is applicable only to thin-film delaminations (≤10 % of the load-bearing skin thickness), restricting its use for surface defect assessment. In [15], the authors present an analytical model that segments composite laminates and accounts for interlaminar stresses, allowing for the evaluation of delamination growth within a fracture mechanics framework. However, the model does not incorporate defects of arbitrary shape, which would enhance its practical applicability. The study in [16] investigates the formation of surface porosity in the outer skins of sandwich panels during the co-curing process. The authors examine how pressure and thermal cycles contribute to this defect. While this research provides valuable insights into surface defects in composite skins, it primarily addresses porosity rather than geometric deformations such as waviness and dents. The work in [17] focuses on the formation mechanisms of dimpling in honeycomb sandwich panels, exploring how mismatched thermal expansion between different structural materials (face sheets, adhesive layers, and core) leads to surface deformations. A combination of finite element analysis (FEA) and an analytical model based on beam theory is used to quantify these deformations. However, the study does not extend to other manufacturing defects such as waviness or bulges of arbitrary shape, which can arise during production and service. The research presented in [18] develops and validates an optimized structural health monitoring system for detecting defects in composite load-bearing skins. The approach integrates experimental data with finite element modelling and machine learning algorithms for damage classification. However, this work primarily focuses on delamination detection and does not consider localized geometric defects such as dents or bulges, limiting its relevance to surface defect evaluation. The study in [19] examines the behaviour of composite skins subjected to combined mechanical and magnetic loading, analysing two conditions: plane stress and uniaxial tension. Numerical modelling is employed to determine critical conditions for skin stability and the onset of wrinkling. While this study provides an in-depth analysis of wrinkling mechanisms in composite laminates, its findings are not directly applicable to the study of dents and bulges in sandwich composite panels. The research in [20] investigates the response of foam-core sandwich panels to local indentation, assessing residual deformations, stress distributions, and dent dimensions in the load-bearing skins after unloading. However, the primary focus remains on the behaviour of the foam core rather than the face sheets themselves. The study in [21] explores the effect of asymmetry in sandwich composite panels on their residual strength following damage. The authors conduct quasi-static indentation tests followed by compression-after-impact experiments. While the study provides valuable insights into the influence of damage on panel strength, it does not examine how geometric imperfections – such as waviness or bulges – affect overall structural performance.

Many of these studies rely on the FEA for defect analysis in sandwich composite panels. While FEA is a powerful tool, it has limitations, including high computational costs and sensitivity to input data accuracy [22, 23]. Additionally, FEA requires a unique model for each defect type, making it difficult to generalize results across different defect geometries [24, 25]. Furthermore, most FEA models assume idealized damage geometries, which limits their applicability to real-world manufacturing deviations such as waviness and bulges of arbitrary shape [26, 27]. Several experimental studies, including [28, 29], provide direct assessments of how localized manufacturing deviations – such as waviness and dents – affect the strength and stability of sandwich composite panels. These studies play a crucial role in validating numerical models, improving the accuracy of FEA simulations and enhancing predictions of structural behaviour under real-world conditions [30, 31]. However, experimental methods have significant drawbacks, including high costs, labor-intensive procedures, and the challenge of replicating all service conditions in a controlled laboratory environment [32, 33].

Despite the extensive research on sandwich composite structures, existing studies do not establish clear threshold values for localized manufacturing deviations such as waviness and dents. Most studies focus either on general mechanical properties or on modelling specific defect types without defining acceptable defect dimensions. This gap between theoretical research and practical quality control requirements in manufacturing and operation underscores the need for further investigation. Some studies, such as [34], have attempted to determine permissible limits for these manufacturing deviations.

The objective of this study is to develop a methodology for defining permissible limits for localized surface deviations – specifically, waviness and dents – in composite skins of sandwich panels. This approach is aimed at defects that can be mitigated through enforced adhesion to the core and is tailored to components with varying degrees of structural criticality based on service conditions.

Research Methodology

As noted above, surface defects that occur during the forming process – such as waviness, bulges, and dents – are often the primary precursors to adhesion failures in sandwich structures and the delamination of composite load-bearing skins from the core. Despite their variety in shape, these defects can generally be classified into two main types: continuous waviness (Fig. 1) and dents (or bulges) of arbitrary shape, which can be approximated with sufficient accuracy by an elliptical form (Fig. 2).

Let us examine these typical defects. The first type, a through-thickness waviness defect relative to the sheet, characterized by a maximum out-of-plane displacement W_{max} (Fig. 1), can be analysed using a simplified beam-strip model with unit width and clamped edges, subjected to a uniformly distributed technological pressure q.

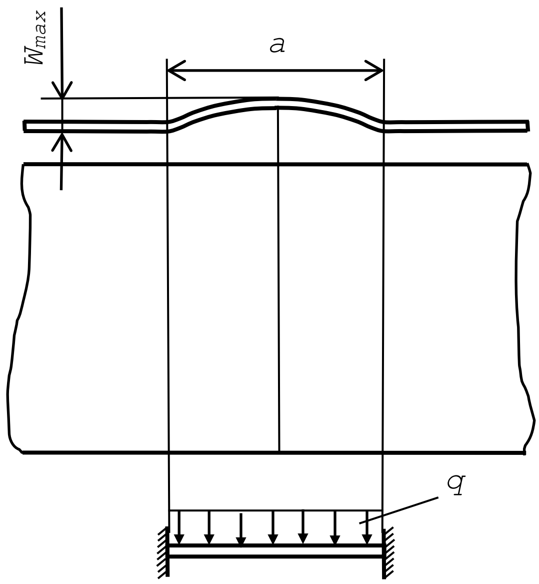

Fig. 1. Technological loading scheme for pressing waviness in composite load-bearing skin to the core

Since, under the specified boundary conditions, the shear stresses induced by bending do not affect the maximum deflection of the beam-strip, we can express it using the well-known equation [35]:

$$W_{max} = \frac{32qa_{lim}^4}{E_x\delta^3}, \tag{1}$$

E_x – the modulus of elasticity of the PCM structure along the beam-strip direction of the waviness; δ – the thickness of the wavy region of the composite skin.

At this stage, the parameter a_{lim} remains unknown. To determine this waviness parameter, we apply the beam-strip model with clamped edges and derive the normal and shear stresses at an arbitrary cross-sectional point $M(0, y)$. Since the maximum bending moments and shear forces occur at the clamped boundaries (x=0 and x=a), the stress distribution can be expressed as follows:

$$\sigma_{x\,q} = \frac{qa^2}{\delta^3}y; \qquad \tau_{xy\,q} = \frac{3}{4}\frac{qa}{\delta}\left(1-\frac{4y^2}{\delta^2}\right). \tag{2}$$

Given that the ultimate state of the orthotropic beam-strip can be adequately described by the Mises-Hill strength criterion [36], we can express the allowable stress level during manufacturing or repair through elastic deformation as follows:

$$\frac{\sigma_{x\,q}^2}{F_x^2} + \frac{\tau_{xy\,q}^2}{F_{xy}^2} \le \psi_q, \tag{3}$$

where F_x – the tensile strength of the PCM along the beam-strip direction; F_{xy} – the shear strength of the PCM.

To analyse the critical dimensions of a defect in the form of an elliptical dent (Fig. 2), we use the well-known solution for an orthotropic elliptical plate [37]:

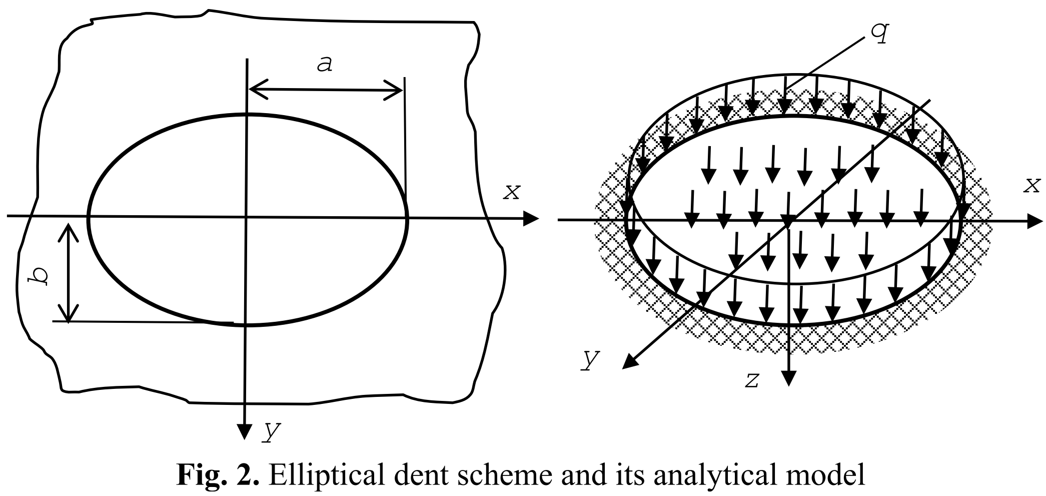

Fig. 2. Elliptical dent scheme and its analytical model

The deflection of the composite skin can be determined using the following relationship:

$$W = \frac{qa^4}{D'}\left(1-\frac{x^2}{a^2}-\frac{y^2}{b^2}\right); \tag{4}$$

$$D' = \frac{\delta^3}{96}\left[3B_{11} + 2\left(B_{12}+2B_{66}\right)\frac{a^2}{b^2} + 3B_{22}\left(\frac{a}{b}\right)^4\right], \tag{5}$$

where B_{ij} – the elastic modulus coefficients; $B_{11} = \dfrac{E_1}{1-\mu_{12}\mu_{21}}$, $B_{22} = \dfrac{E_2}{1-\mu_{12}\mu_{21}}$, $B_{12} = \dfrac{E_1\mu_{21}}{1-\mu_{12}\mu_{21}}$, B_6=G_{12}; E_1, E_2 – the elastic moduli of the PCM along the semi-axes *a* и *b*; G_{12}, μ_{12}, μ_{21} – shear modulus and Poisson's ratios.

The maximum stresses acting at the critical points of the elliptical dent $z = \pm\delta/2$ can be expressed as

$$\sigma_x = \pm\frac{\delta}{2}\left(B_{11}\frac{\partial^2 W}{\partial x^2} + B_{12}\frac{\partial^2 W}{\partial y^2}\right);$$
$$\sigma_y = \pm\frac{\delta}{2}\left(B_{12}\frac{\partial^2 W}{\partial x^2} + B_{22}\frac{\partial^2 W}{\partial y^2}\right); \tag{6}$$
$$\tau_{xy} = \pm\delta\, B_{66}\frac{\partial^2 W}{\partial x \partial y}.$$

Differentiating the deflection equation (4) and substituting the results into (6) at $z = \delta/2$, we obtain:

$$\sigma_x = \frac{2qa^2\delta}{D'b^2}\left[B_{11}\left(3x^2\frac{b^2}{a^2} + y^2 - b^2\right) + B_{12}\left(3\frac{a^2}{b^2}y^2 + x^2 - a^2\right)\right];$$
$$\sigma_y = \frac{2qa^2\delta}{D'b^2}\left[B_{12}\left(3x^2\frac{b^2}{a^2} + y^2 - b^2\right) + B_{22}\left(3\frac{a^2}{b^2}y^2 + x^2 - a^2\right)\right]; \tag{7}$$
$$\tau_{xy} = -\frac{8qa^2\delta}{D'b^2}B_{66}xy.$$

The Hill strength criterion [36] for the analytical model of an elliptical dent in a composite plate is expressed as:

$$\frac{\sigma_{xq}^2}{F_x^2} - \frac{\sigma_{xq}\sigma_{yq}}{F_x^2} + \frac{\sigma_{yq}^2}{F_y^2} + \frac{\tau_{xyq}^2}{F_{xy}^2} \le \psi_q. \tag{8}$$

Results and Discussion

To determine the ordinate *y* at which the stresses from equation (2) maximize the left-hand side of the Hill strength criterion (3) in the case of the technological pressing scheme for eliminating waviness, we need to identify the maximum value of the function *f*(*y*), which represents the left-hand side of equation (3) for given values of σ_{xq} and τ_{xyq} from equation (2). Thus, we define the function:

$$f(y) = \frac{q^2a^2}{\delta^2}\left[\frac{9y^4}{\delta^4F_{xy}^2} - \frac{y^2}{\delta^2}\left(\frac{9}{2F_{xy}^2} - \frac{a^2}{\delta^2F_x^2}\right) + \frac{9}{16F_{xy}^2}\right]. \tag{9}$$

It is straightforward to establish that the maximum of *f*(*y*) corresponds to the coordinate *y*=0, where σ_{xq}=0. At this point, the value of *f*(*y*) is given by:

$$f\left(y\right)\Big|_{y=0} = \frac{9}{16}\frac{q^2 a^2}{\delta^2 F_{xy}^2}. \tag{10}$$

Since we are interested not necessarily in the absolute maximum, but in the largest value of *f*(*y*) within the interval $-\delta/2 \le y \le \delta/2$ (which is equivalent to the interval $0 \le y \le \delta/2$ due to the symmetry of the function), we need to compare the values of $f\left(y\right)\Big|_{y=0}$ and $f\left(y\right)\Big|_{y=\delta/2}$. Considering that $y = \delta/2$, the shear stress component $\tau_{xy\,q} = 0$, we obtain

$$\frac{f\left(y\right)\Big|_{y=0}}{f\left(y\right)\Big|_{y=\delta/2}} = \frac{9}{4}\left(\frac{\delta}{a}\right)^2\left(\frac{F_x}{F_{xy}}\right)^2. \tag{11}$$

Considering the range of practically detectable waviness defects $a/\delta > 5$ [17, 22, 34] and the possible modulus ratios F_x/F_{xy} of existing PCM within the range $3 \le F_x/F_{xy} \le 5$ [38], we observe that certain cases may arise where $f\left(y\right)\Big|_{y=0} < f\left(y\right)\Big|_{y=\delta/2}$ and $F\left(y\right)\Big|_{y=0} > F\left(y\right)\Big|_{y=\delta/2}$.

Thus, the critical factors determining the permissible limit for a waviness-type defect are either the maximum normal stresses at the cross-section point $M\left(0,\, \delta/2\right)$ or the maximum shear stresses at critical cross-section $M\left(0,\, 0\right)$. By substituting the values of $\sigma_{x\,q}$ and $\tau_{xy\,q}$ from equation (2) into the Hill strength criterion given in equation (3), we derive the maximum allowable waviness size for a given PCM, manufacturing process pressure *q*, and structural criticality level of the component:

$$min\begin{cases} a_{lim} \le \dfrac{4}{3}\dfrac{\delta F_{xy}}{q}\sqrt{\psi_q}; \\ a_{lim} \le \delta\sqrt[4]{\dfrac{4\psi_q F_x^2}{q^2}}. \end{cases} \tag{12}$$

where, ψ_q – the maximum stress intensity factor at the characteristic point of the component.

In [39], the maximum allowable stress intensity for composite components was determined based on the type of structure and its criticality, using aerospace applications as an example. The values, which are influenced by the manufacturing process, are categorized as follows: low-loaded structures $0 \le [\psi_q] \le 0.223$; moderately-loaded structures $0.223 \le [\psi_q] \le 0.33$ and highly-loaded structures $0.33 \le [\psi_q] \le 0.75$. These values define the acceptable stress intensity levels for different classes of composite components, ensuring reliability in accordance with their operational requirements.

At the same time, the minimum deflection of the waviness must not exceed the value determined by equation (1) when considering the minimum value of a_{lim} from equation (7).

In the case of an elliptical dent, the study [34] demonstrated that the maximum bending moments (and, consequently, the corresponding normal stresses) occur at the boundary of the elliptical plate at point $M\left(0,\, b\right)$ if $B_{11} < B_{22}\, a^2/b^2$, at point $M\left(a,\, 0\right)$ if $B_{11} > B_{22}\, a^2/b^2$.

It should also be noted that the maximum shear stresses will likewise be located at the boundary of the plate, as evident from equation (7). Therefore, similar to the waviness defect, we determine the coordinates of the critical point $M\left(a\xi,\, b\sqrt{1-\xi^2}\right)$ where $-1 \le \xi \le 1$ the left-hand side of the strength criterion (8) reaches its maximum value. Due to symmetry, it is sufficient to consider the interval $0 \le \xi \le 1$. It can be easily shown that the maximum value of the function $f(\xi)$ on the right-hand side of criterion (8), given the stress components σ_{xq}, σ_{yq} and τ_{xyq} determined by equation (7), corresponds to $\xi = 0$, where $\tau_{xyq} = 0$.

Since the goal is not to determine the maximum but rather the greatest value of $f(\xi)$, it is necessary to compare the values $f(\xi)\big|_{\xi=0}$ and $f(\xi)\big|_{\xi=1}$. However, a comprehensive analysis of these values across all practically possible combinations of physical and geometric parameters is infeasible. Therefore, as in the case of the waviness defect, it is reasonable to use two approximate evaluation formulas for $a_{lim}\big|_{\xi=0}$ and $a_{lim}\big|_{\xi=1}$, selecting the smaller of the two as the permissible limit. Based on this approach, by substituting the stress values from equation (7) into the left-hand side of criterion (8) at points $M(0, b)$ and $M(a, 0)$, and performing the necessary transformations, we obtain:

$$a_{lim} \le \frac{\delta}{8c} \sqrt[4]{\frac{\psi_q \left[3B_{11} + 2\left(B_{12} + 2B_{66}\right)c^2 + 3B_{22}c^4\right]^2}{36q^2 \left[\dfrac{B_{12}\left(B_{12} - B_{22}\right)}{F_x^2} + \dfrac{B_{22}^2}{F_y^2}\right]}} \text{ if } B_{11} < B_{22}c^2; \tag{13}$$

$$a_{lim} \le \frac{\delta}{8} \sqrt[4]{\frac{\psi_q \left[3B_{11} + 2\left(B_{12} + 2B_{66}\right)c^2 + 3B_{22}c^4\right]^2}{36q^2 \left[\dfrac{B_{11}\left(B_{11} - B_{12}\right)}{F_x^2} + \dfrac{B_{12}^2}{F_y^2}\right]}} \text{ if } B_{11} > B_{22}c^2, \tag{14}$$

where $c = a/b$ – the relative defect size.

This formulation allows for a practical assessment of the maximum permissible defect size, ensuring compliance with the structural strength criteria for a given material and loading condition.

The numerical study was conducted using a flat rectangular panel with dimensions 140×70×18 mm as a representative model for analysing the effect of localized surface defect. This panel was made of UT-900-2.5 woven carbon fiber composite based on EDT-69N binder with the characteristics given further: ultimate tensile strength along the grain F_x=917 MPa; ultimate tensile strength across the grain F_y=881 MPa; modulus of elasticity along the grain E_x=69 GPa; modulus of elasticity across the grain E_y=67 GPa; ultimate shear strength in the laying plane F_{xy}=75 MPa; shear modulus in the laying plane G_{xy}=5.5 GPa; Poisson's ratio μ_{xy}=0.32; layup pattern – $[0°/90°/0°/90°]_s$ [34]. The critical defect size a_{lim} was determined for a preselected maximum stress intensity factor [ψ_q]=0.75, considering the relative defect area $\overline{S} = S_d/S_0$ and defect depth $\overline{\delta} = \delta_d/\delta_0$. The results are presented in Table 1.

Table 1. Values of the critical defect size a_{lim} for a preselected maximum stress intensity factor [ψ_q]=0.75 depending on the relative defect area $\overline{S} = S_d/S_0$ and depth $\overline{\delta} = \delta_d/\delta_0$

Relative defect area $\overline{S}$ / Relative defect depth $\overline{\delta}$	0.01	0.04	0.09
0.125	4.46 mm	9.99 mm	11.59 mm
0.250	4.46 mm	9.92 mm	17.74 mm
0.375	4.46 mm	9.92 mm	14.94 mm
0.500	4.46 mm	9.92 mm	14.94 mm

It is important to note that the elimination of defects whose critical dimensions are determined by equations (13) and (14) is only possible if proper air evacuation from beneath the defect cavity is ensured [9, 10, 13].

If the maximum deflection at the center of the waviness satisfies the inequality:

$$W_{max} \le \frac{96qa_r^4}{\delta^3\left[3B_{11}+2\left(B_{12}+2B_{66}\right)c^2+3B_{22}c^4\right]}, \tag{15}$$

where a_r – the actual half-size of the defect along the x-axis, then the defect can be eliminated using technological methods.

Conclusions

This study investigated localized technological deviations in the surface of load-bearing skins of sandwich composite panels, specifically in the form of waviness and dents. The maximum permissible defect sizes that can be eliminated by forced adhesion to the core were determined for components with varying levels of structural criticality under operational conditions.

It should be noted that forced compression of dents or bulges induces pre-stress in the defect zone of the composite skin, which may reduce its load-bearing capacity during operation. This effect highlights the need for further research to assess its impact on structural performance.

With the developed methodology, it is possible to address critical practical challenges, including the performance degradation of polymer composite panel structures due to delaminations and the identification of optimal repair methods for such defects.

The findings of this study can contribute to the development and improvement of repair techniques and quality control methods for composite structures, enhancing their reliability and durability.

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