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# The effect of shear on the local indentation and failure of sandwich beams with polymeric foam core loaded in flexure

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ABSTRACT

Three-point and four-point bending tests were carried out on sandwich beams consisting of glass-fibre-reinforced plastic facings and a Divinycell H60 foam core. During the tests, final failure was invariably precipitated in the upper facing at the points of load introduction, whereas no other failure modes typically exhibited by a sandwich structure were observed. From the experimental results, the critical load causing final failure was found to be independent of the overall bending moment $M$ and local force $P_l$ alone, in contrast with the hypotheses of the theoretical models presently available in the literature. On the contrary, for a given $M/P_l$ ratio adopted in the tests, the critical conditions were achieved more easily in the case of four-point than under three-point bending. A possible explanation of the observed phenomenon was given by calling into question the influence of the shear force, that may contribute to the sandwich local collapse. An empirical failure criterion, taking into account the bending moment, the local force and the shear force, was found to reasonably match the experimental results, although the physical meaning of one of the parameters appearing in the model formulation is matter of further research.



## 1. Introduction

Sandwich panels are increasingly used in load-bearing constructions, including shipbuilding, aerospace, civil industry, high-speed transportation [1], etc., due to their favourable flexural stiffness and strength coupled with low weight. However, the experimental and theoretical studies conducted on these structures have highlighted a multiplicity of competing failure mechanisms that result in final collapse, which makes their design and optimization significantly complex.

When a typical sandwich made of two thin and strong facings and a light, low density foam core is subjected to flexure, the overall bending moment is carried by the facings, where two normal forces arise, whereas the shear force is mainly carried by the core [2,3]. Consequently, possible tension/compression failures in the facings and shear failures in the core are expected. In addition, the sandwich facing subjected to compression may undergo wrinkling and debonding may occur at its interface with core. Finally, local bending of the facings at the points of load application, responsible for core yielding and facing collapse, may take place, thus resulting in local indentation.

At present, simple formulae for stress distribution in the facings and core are available [2,3]: these allow an accurate prediction of the critical conditions for facings failure in tension/compression and shear failure in the core. The analytical tools for calculating wrinkling are less reliable [4], since this local elastic instability mode can involve various buckled shapes, not easily predictable "a priori" [2]. Indeed, the situation is far more complicated when local indentation is concerned, despite the efforts of the researchers in this field and the closed-form formulae proposed in the literature [5–9].

In this paper, focused on the final collapse of sandwich structures induced by local indentation, some analytic solutions available to this aim are recalled. The results of three-point bending (3PB) and four-point bending (4PB) tests are then presented and discussed, highlighting the limitations of the formulations available nowadays and the potential role of shear force in determining indentation. Finally, an original failure criterion, taking into account the bending moment, the local force and shear force is established.

## 2. Sandwich local indentation

Fig. 1 schematically depicts the situation occurring in correspondence of a point of load application on a sandwich beam, with

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equal facings and unit width, subjected to flexure. The overall flexural moment $M$ bends the beam about its neutral axis (not shown in the figure). At the same time, the force $P_l$ applied by the loading roller locally bends the upper facing about its own neutral axis, also compressing the core beneath. Limiting the attention to a sandwich with polymeric foam core and composite facings, under these loading conditions the following phenomena, resulting in failure at the point of load application, may occur: (a) the upper facing collapses in pure compression (also labelled as "microbuckling") without significant core plasticization or yielding; (b) the core undergoes plasticization without facing failure; (c) the core yields, causing the flexural failure of the upper facing. While failure (a) is mainly controlled by $M$, thus belonging to the global failure modes, (b) and (c) are also determined by $P_l$, and can be then classified as "indentation failures".

Of course, in order to predict the actual failure mode which is likely to occur, an effective method for the evaluation of the stress field in both the facing and the core is required. This is straightforward as concerns the moment $M$, which, according to the classical sandwich theory [2,3], gives rise to normal stresses $\sigma_M(z)$ given by:

$$\sigma_M = \frac{ME_i}{D} z \tag{1}$$

where $z$ is the distance from the neutral axis of the sandwich (Fig. 1), $E_i$ the elastic modulus of the concerned material (hereinafter the indexes $i = f,c$ will be used for facings and core, respectively), and $D$ the flexural rigidity, given by:

$$D = \frac{E_f t_f^3}{6} + \frac{E_f t_f d^2}{2} + \frac{E_c t_c^3}{12} \tag{2}$$

In Eq. (2), $t_f$, $t_c$ are the facing and core thickness, respectively, and $d$ is the distance between the facings centroids (Fig. 1).

As will be shown later in this work, in all the experimental tests whose results are discussed here, the catastrophic failure of the sandwich was induced by the breakage of the upper facing, therefore, in what follows, the attention will be limited to the analysis of the stresses arising in this component. According to Eq. (1), the maximum normal stress $\sigma_{\mathrm{Mmax}}$ arising here is given by:

$$\sigma_{\mathrm{Mmax}} = \frac{ME_f}{D} \cdot \left( t_f + \frac{t_c}{2} \right) \tag{3}$$

If the core is antiplane ($E_c = 0$) and the facings are thin ($t_f \ll t_c$), $M$ is uniquely carried by the facings [2,3] through two forces $F$ which, from equilibrium, hold:

$$F = \frac{M}{d} \tag{4}$$

and Eq. (3) becomes:

$$\sigma_{\mathrm{Mmax}} \approx \frac{F}{t_f} = \frac{M}{t_f d} \tag{5}$$

Calculating the state of stress in the upper facing deriving from the local force $P_l$ is a quite intricate task, involving appropriate hypotheses on the core behaviour. In early works, this problem was treated by modelling the facing as a linear elastic plate or beam resting on a fully backed linear Winkler foundation [6,10], yielding [11]:

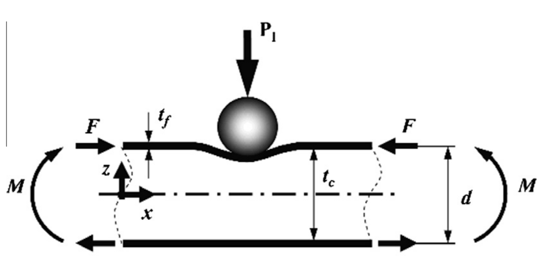


**Fig. 1.** Local deformation and loads in the facings of a sandwich beam loaded in flexure.

$$\sigma_p = \frac{3P_l}{2t_f^2} \cdot \sqrt[4]{\frac{4D_f}{k}} \tag{6}$$

where $\sigma_P$ is the maximum stress in the facing, $D_f$ the flexural rigidity of the facing, and $k$ the modulus of foundation, given by:

$$k = \frac{E_c}{t_c} \tag{7}$$

Soden [12], modelling the core as a rigid-perfectly plastic Winkler foundation, derived a simple expression correlating $P_l$ with $\sigma_P$:

$$\sigma_p = \frac{9P_l^2}{16t_f^2 X_{cc}} \tag{8}$$

where $X_{cc}$ is the core compression strength.

An analytic, segment-wise procedure accurately representing the actual core compression curve in the case of a fully backed sandwich beam under localized load was proposed by Minakuchi et al. [13] for honeycomb cores, and implemented for foam core materials by Pitarresi and Amorim [14]. In order to obtain the critical load for facing failure, the solution to a system of equation must be sought. Unfortunately, at the present this solution is not available in closed form.

As previously noted, the solutions developed in [6,10–14] are strictly applicable to fully backed sandwich structures only. Nevertheless, with the aim to predict the conditions for facing microbuckling of simply supported beams, some authors [8,15,16] have successfully used superposition approaches, simply summing the stresses due to the global moment (Eqs. (3) or (5)) and to the local deflection (Eqs. (6) or (8)). The critical conditions are achieved when the maximum stress in the facing reaches the compression strength $X_{cf}$ of the facing material:

$$X_{cf} = \sigma_{\mathrm{Mmax}} + \sigma_p \tag{9}$$

From Eq. (9), if $\sigma_P \gg \sigma_{\mathrm{Mmax}}$, a facing failure can be classified as "indentation failure". On the contrary, an increase of $\sigma_{\mathrm{Mmax}}/\sigma_P$ (i.e., $M/P_l$) heightens the probability of a global failure, not necessarily occurring at the point of load application.

It has been recognized that the superposition method has some limitations when employed in the analysis of sandwich plates [17,18], mainly due to the fact that they neglect the interaction between global and local effects [14] and they disregard the actual boundary conditions at the lower facing [19]. The latter approximation results in an inaccurate evaluation of the foundation modulus when Eq. (7) is adopted [19,20]; this inaccuracy was overcome in the model developed by Steeves and Fleck [9], who considered a beam in 3PB. The authors postulated that, due to the combined action of $F$ and $P_l$ in Fig. 1, the upper facing may buckle, bringing to core softening. By assuming a rigid-ideally plastic, Winkler-type core, and relying on appropriate boundary conditions, Steeves and Fleck found the shape of the facing as a function of $P_l$. According to the developed model, $P_l$ does not increase monotonically with increasing local deformation; rather, a maximum value $P_l^*$ of the local load, beyond which the load decreases steadily, is achieved. Therefore, $P_l^*$, given by:

$$P_l^* = t_f \cdot \sqrt[3]{\frac{\pi^2 d E_f X_{cc}^2}{6L_3}} \tag{10}$$

was assumed as a critical load resulting in failure. $X_{cc}$ in Eq. (10) is the compression strength of the core material, whereas the meaning of the symbol $L_3$ is clarified in Fig. 2a.