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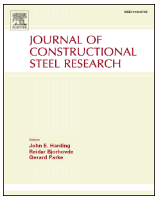

Exact solutions and experimental research for continuous triple- equal-span fully profiled sandwich panels

Dimitrios Moutaftsis *, Martin D. Heywood, Raymond G. Ogden

Faculty of Technology, Design and Environment, Oxford Brookes University, Oxford, UK

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The paper presents a set of newly developed exact analytical solutions for triple- equal-span arrangements of panels with fully profiled faces in flexure. Their derivation was based on a set of general fundamental equations retrieved from the governing differential equations for sandwich beams. Specifically designed tests of single- and triple-span fully profiled panels with steel faces (outer fully profiled and inner lightly profiled) and polyisocyanurate cores were conducted to investigate the response with regards to stiffness and initial failure, which are critical for serviceability limit states. Good agreement between test and theory was demonstrated, with safe results in all cases. The new design method permits the elimination of a significant amount of conservatism compared to current methods.

1. Introduction

Sandwich panels represent a form of lightweight composite construction, comprising a rigid layer of insulation between and adhered to two thin layers of metal sheeting, forming a single manufactured unit. The system benefits from a high strength-to-weight ratio, good structural and thermal performance, rapid speeds of production (up to 12 m/min), and good air-tightness characteristics. They are also relatively simple to handle and install, have good durability and offer many architectural possibilities. The market for sandwich panels is large and well-established both in relation to roof and wall applications.

The metal faces are typically made of steel with a thickness range between 0.3 mm and 0.7 mm, or less commonly aluminium. Face geometry can be flat, micro-ribbed (often referred to as 'satinlined'), lightly profiled or fully profiled. Roof applications typically comprise a fully profiled external sheet and a lightly profiled internal (liner) sheet, while wall applications mostly comprise flat, lightly profiled or micro-ribbed geometries. The core is typically made of polyisocyanurate (PIR), polyurethane (PUR), extruded polystyrene (EPS) or mineral wool (slabs or lamellas). In the UK, PIR and mineral wool are the most extensively used sandwich panel core materials, with the latter being used primarily for wall applications.

Sandwich panels may be installed as single-, double- or multi-span arrangements. Multi-span continuous panels are increasingly popular, particularly for roof applications, due to the greater efficiency of manufacturing, transport and installation (fewer parts to handle). They are also superior to single- and double-span panels in terms of structural performance and air-tightness.

In the UK, design calculations for sandwich panels are typically produced by manufacturers and presented in the form of load versus equal-span tables for single-, double- and multi-span arrangements. Triple-span arrangements are used as sufficiently representative of multi-span conditions. For fully profiled panels, while exact analytical design solutions are available for both single- and double-span arrangements with equal spans under distributed load [1], there is a lack of guidance for triple- and multi-span cases. Established finite element modelling methods [2,3] are accurate and virtually applicable for any case,

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Abbreviations: A_c, area of lightweight core; A_{F1}, area of steel face (1); A_{F2}, area of steel face (2); B, bending stiffness; B_D, bending stiffness of 'flange' part; B_S, bending stiffness of 'sandwich' part; d_C, clear core depth; d_2, depth of outer profile; d_{11}, position of outer profile's neutral axis; d_{21}, position of inner profile's neutral axis; e, distance between centroids of faces; E_{F1}, Young's modulus for steel face (1); E_{F2}, Young's modulus for steel face (2); G_C, shear modulus of the core; G_{eff}, effective shear modulus of the core; I_{F1}, moment of inertia of steel face (1); I_{F2}, moment of inertia of steel face (2); L, span of the panel; M_{sup}, applied bending moment at the support; M_D, bending moment in 'flange' part; M_{F1}, bending moment in 'flange' part – steel face (1); M_{F2}, bending moment in 'flange' part – steel face (2); N_{F1}, axial force in steel face (1); M_S, bending moment in "sandwich" part; N_{F2}, axial force in steel face (2); P, point load applied at span; q, uniformly distributed load on the panel; V_{F1}, shear force in steel face (1); V_{F2}, shear force in steel face (2); V_S, shear force in core; W, total applied load in one span; α, parameter; β, parameter; δ, deflection; ε, location of applied load within the panel (ratio between 'distance of applied point load from panel end' and 'length of panel'); ε_i, parameter of stress distribution; λ, parameter; ξ, location within the panel (ratio between 'distance panel end' and 'length of panel'); σ_{Fij}, axial stress in the steel sheet; τ_C, shear stress in the core; τ_{Fi}, shear stress in the steel sheet; x, coordinate along the longitudinal axis.

* Corresponding author.
E-mail address: dim.moutaftsis@gmail.com (D. Moutaftsis).

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however they require significant computational effort and specialist knowledge, whilst currently available approximate solutions provide conservative results to ensure safety [4,5]. This observation has been made from the analysis of a large number of structural tests for commercial purposes by the authors. While discrepancies between theory and practice may often be due to the reliability of material properties, they also reflect the approximations implicit in existing theory [1,4,5]. This is particularly acute for continuous arrangements.

Accurate quantification of exact bending moments and stress distribution across continuous sandwich panels is very important for design and specification. Typically working load failures occur at intermediate support locations where maximum bending moments are developed. Reliable global analysis is therefore particularly beneficial.

The aim of this paper is to present and validate a set of reliable exact analytical solutions for bending problems of continuous triple-span fully profiled sandwich panels with equal spans. The developed solutions can then be used by designers and specifiers to accurately estimate the distribution of bending moments and stresses by incorporating them into conventional computer tools such as spreadsheets, without the need for specialist software. The focus is on the design of sandwich panels with one face fully profiled and one lightly profiled, i.e. systems used primarily (but not exclusively) for roof applications.

2. Literature review of bending problems' solutions development

The structural performance of sandwich panels relies on composite action between the core and the metal sheets. The behaviour of these panels is relatively simple to analyse using conventional principles of structural mechanics. Simple beam and plate theory, however, cannot be used. This is because the shear flexibility of the core affects the global and local (cross sectional) stress distribution, hence is required to be taken into account.

For the purpose of structural analysis, sandwich panels may be divided into two categories:

- Panels with at least one face fully profiled (typically referred to as 'fully profiled' panels).
- Panels with flat and/or lightly profiled faces.

For fully profiled sandwich panels, both the stiffness of the profiled faces and the flexibility of the core must be taken into account, creating a local static indeterminacy within the cross section even for single-span cases. This is not the case for panels with flat or lightly profiled faces, where the bending stiffness of the faces is ignored and the problem is statically determinate single span cases. For continuous fully profiled panels with two or more spans, a global static indeterminacy exists in addition to the local, making the problem of calculation of stress resultants even more complicated. Stamm and Witte [6] have demonstrated explicit exact solutions based on governing differential equations by Allen [7]. These were used to estimate the distribution of bending moments and shear forces across the length of single span sandwich panels when under uniformly distributed load, point load at any location and uniform temperature load.

Davies [2] highlighted the exact analytical solutions by Stamm and Witte [6] for single-span cases and presented a novel finite element model which yields highly accurate results. Davies [3] later extended this model to account for in-plane axial loading due to thermal bowing.

Berner [5] presented approximate analytical solutions for single-span and graphical solutions for continuous double- and three-span cases, which have limited ranges of application for continuous spans as discussed by Heywood et al. [4]. The range of depths covered by the graphs is insufficient to provide the levels of insulation necessary to satisfy modern regulations for conservation of energy in buildings.

Davies et al. [8] presented the exact solutions from both Stamm and Witte [6] and Davies [2], together with the approximate analytical and graphical solutions by Berner [5] for single-, double- and multi-span arrangements. Particularly for continuous arrangements, Davies et al. [8] recommend that if an exact solution is to be found for double- or multi-span arrangements this may be done using the fundamental equations for single-span under distributed, point or thermal load and superposing the various loading arrangements.

ECCS Recommendations [1] offered, for first time, analytical solutions for double-span continuous panel arrangements of equal spans for both uniformly distributed structural and thermal loads. The proposed equations are exact and offer designers the choice to depart from the approximate graphical solutions provided by Berner [5], which are also presented in ECCS Recommendations [1], at the cost of additional, but relatively simple, computational effort. Furthermore, the exact solutions are not limited by the dimensions of the panel and, therefore, are applicable to any geometry. The case of thermal loading is however presented with sign errors that yield erroneous results.[1] No solutions are offered for multi-span arrangements, but the designer is prompted to use the double-span case instead, an approach which yields conservative results.

EN 14509:2013 [9] is the current European Standard for manufacturing, design and testing of sandwich panels. It is an evolution of ECCS Recommendations [1] and an update to the superseded EN 14509:2006 [10]. The superseded standard presented the approximate solution for single-span cases under distributed thermal and structural load as shown by Berner [5].

EN 14509:2013 [9] substituted the approximate for the exact solution which relies on the early literature of Stamm and Witte [6]. There is an absence of guidance for continuous panel cases within the standard. Instead, designers are prompted to seek further guidance from external sources such as Davies et al. [8].

Heywood et al. [4] developed a set of approximate solutions for double- and multi-span span arrangements to extend the range of the graphs developed by Berner [5]. The aim was to offer guidance for fully profiled panels with modern specifications and increased core thicknesses. The guidance was derived from finite element analysis and structural testing to demonstrate the validity of the output. The main drawback of that particular guidance is that it is semi-empirical and conservative.

Gosowski and Gosowski [11,12] developed distributional solutions which take into account the flexibility of the supports. The authors demonstrated that changes in the bending moment distribution occur when the support flexibility is varied and are particularly useful for cases of arbitrary spaced supports and when the elasticity of the panel's supports is known.

All the above-mentioned methods concern the elastic stage of the panel response. The use of elastic methods is appropriate for Ultimate Limit States (ULS) and Serviceability Limit States (SLS) checks according to EN 14509:2013 [9]. For single-span arrangements, the response is elastic until the resistance of the sheets in tension or compression or the resistance of the core in shear or compression is exceeded and ultimate failure occurs (ULS). SLS conditions refer to deflection limitations only. For continuous panel arrangements, EN 14509:2013 [9] categorises failure of the supports at either bending (compression or tensions yielding of the sheets) or core crushing as SLS (together with deflection limitations at the spans). This is because the aforementioned failure modes do not lead to ultimate failure and global collapse. The response is elastic until these modes occur. Hence, the SLS term in EN 14509:2013 [9] refers to the maximum working load and prevention of any kind of failure at that magnitude is necessary. Since this SLS failure modes occur prior to failure in the spans, they usually govern the design of the panel. It is worth highlighting that EN 14509:2013 [9] uses a load factor of 1.0 for the working load (SLS).

For ultimate failure of continuous arrangements, a pseudo-plastic approach is adopted by EN 14509:2013 [9] in which it is assumed that a plastic hinge with zero moment capacity is formed at the intermediate support at the initial working load failure after which

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[1] Terms ε_5, ε_7 and M_{F1} should be calculated with a sign opposite than the one presented in ECCS Recommendations (2000)