



An energy-consistent framework for shear correction in corrugated sandwich plates with soft cores

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ABSTRACT

Accurate evaluation of the transverse shear correction factor is essential for reliable modelling of sandwich plates with soft cores, particularly when first-order shear deformation theories are employed. Classical shear correction factors, usually derived for homogeneous or weakly heterogeneous plates, may become inadequate for corrugated sandwich structures with pronounced stiffness contrast, where the soft core tightly fills the profiled space between corrugated facings. This study addresses the question of how an energy-consistent shear correction factor can be identified for such cross-sections without resorting to a full three-dimensional finite element model. A unified framework is proposed, combining a closed-form layered formulation with a pixel-based formulation of the cross-section. The layered solution provides a transparent analytical baseline for flat or homogenizable sandwich configurations, whereas the pixel-based formulation enables direct treatment of corrugated geometries in which the soft core fully occupies the profiled space formed by the corrugated facings. The method is based on strain-energy equivalence and evaluates the transverse shear stiffness from the spatial distribution of geometry and material properties. The results show that the identified shear correction factor is strongly affected by the reference shear modulus, material contrast, and core-dominated shear-energy localization. The obtained values therefore should be interpreted as energy-consistent stiffness scaling factors rather than universal constants. The proposed framework is computationally lightweight and can be directly incorporated into Mindlin–Reissner plate and shell models. Its scope is global stiffness correction; detailed local stress fields, thickness-stretching effects, and full three-dimensional validation remain subjects for future work.

1. Introduction

Sandwich plates with soft cores are widely used in lightweight structural applications because they combine high bending stiffness, low mass, and considerable design flexibility [1–4]. Typical engineering applications include building envelopes, lightweight floors, façade and roof panels, transport structures, protective elements, and prefabricated structural components in which serviceability is often governed not only by bending stiffness but also by transverse shear flexibility [5–7]. This issue becomes particularly important when thin metallic facings are combined with a low-stiffness polymeric, mineral, or foam-like core. In such structures, first-order shear deformation theories (FSDT), including Mindlin–Reissner plate and shell formulations, are frequently used because they provide an efficient reduced-order alternative to full three-dimensional modelling while retaining the essential contribution

of transverse shear deformation [8,9].

A critical ingredient of FSDT-based models is the shear correction factor, which ensures energetic consistency between the simplified kinematic assumptions and the actual distribution of transverse shear stresses. Classical values of the shear correction factor are usually derived for homogeneous plates or idealized cross-sections and are often adopted in practice without modification. While such assumptions may be acceptable for moderately heterogeneous structures, they become questionable for sandwich plates characterized by strong stiffness contrasts between layers and complex geometric features [10,11]. For homogeneous rectangular plates, the classical value of the shear correction factor may provide a convenient engineering approximation. However, in sandwich plates with stiff facings and a highly compliant core, the transverse shear energy is not distributed in the same way as in a homogeneous cross-section. Instead, it may be concentrated in the soft core

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or in the profiled regions formed by the corrugated facings and fully occupied by the core material. Consequently, the shear correction factor cannot be treated as a purely tabulated constant, but should be identified consistently with the adopted reference shear stiffness and the actual cross-sectional geometry.

To obtain reliable transverse stresses, the use of FSDT requires an appropriate shear correction factor. This factor was introduced by Timoshenko over 100 years ago, but the problem of determining its appropriate value has been discussed in the literature to this day. A comprehensive review of the coefficients used in beam vibration problems was presented by Kaneko [12]. The coefficients used in static problems for various beam cross-sections were derived by Cowper [13]. It is worth noting that the value of the shear correction coefficient depends not only on the geometry of the beam cross-section and the variability of the material properties of this cross-section, but also on the analyzed mechanical problem, support and loading conditions, as well as the method used to determine this coefficient [14–16]. For example, the issue of determining the shear coefficient in the case of creep-damage analysis of homogeneous and isotropic beams, plates and shells was presented in Ref. [17]. Another interesting case - the dependence of the shear correction factor on temperature was discussed in Ref. [18]. The issue was presented in the context of application of functionally graded materials in thermal environments.

The problem of determining the appropriate shear correction factor is particularly evident in the case of sandwich plates with corrugated metallic facings combined with soft cores. Corrugation is frequently introduced to enhance bending stiffness, improve stability, or facilitate manufacturing. Deep-profiling of the facings also improves the shear strength of the plate and reduces the effect of core creep. Corrugating the facing and filling the entire space between the facings with core material leads to a geometrically complex cross-section, where the soft core continuously fills the profiled regions formed by the corrugated facing. This means that for a given coordinate at the cross-section height, we can have areas of metal facing, flexible core, or empty space (outside the cross-sectional area of the plate). In these cases, the classical notion of clearly separated layers with piecewise-constant material properties is no longer valid. Instead, the transverse shear load is transferred through a complex network of stiff metallic corrugation folds and shear-deformable core regions, giving rise to highly non-uniform shear stress and strain energy distributions. This gives rise to the central research question addressed in this paper: how can the transverse shear stiffness of a corrugated sandwich plate, in which a soft core fully fills the profiled space between the facings, be represented in a standard FSDT model by a single energy-consistent correction factor? Answering this question is important for reduced-order numerical models, design-oriented parametric analyses, and optimization studies, where a fully resolved three-dimensional model of each corrugation pattern would be computationally inefficient.

When FSDT or similar theories are used for the analysis of layered elements, the problem of determining the appropriate shear correction factor is even more complex than in the case of the analysis of homogeneous elements. A general expression to compute static shear correction factors for beams with arbitrary lay-up configurations was presented in Ref. [19], where an energy equivalence principle was used. The identification of the shear correction coefficients for the FSDT models representing elements made of functionally graded materials was presented in Ref. [20]. In this paper, the shear coefficients were studied by considering the shear deformation energy. In Ref. [21], shear correction factors were derived for beams made of functionally graded material (FGM) using the variational asymptotic method (VAM). This formulation permits solutions for a large class of gradation models of FGM. An analytical model to study the effect of porosity on the shear correction factors of functionally graded porous beams was discussed in Ref. [22]. For the conducted analysis, uneven and logarithmic-uneven porosity functions were adopted to be distributed through the thickness of the FGP beams. An interesting discussion for defining

explicit/implicit layer-wise shear correction factors for dynamic analysis of circular sandwich plates with functionally graded face sheets/cores was presented in Ref. [23]. Another case, namely a cross-section containing a thin and flexible core layer, was analyzed in Ref. [24], where a new expression for the effective shear stiffness was derived. In Ref. [25], shear correction factors were discussed in the context of the Reissner–Mindlin kinematics enriched by warping displacements interpolated with layer-wise cubic functions through the thickness of the layered shells. A new formulation of continuous transverse shear stress field for static and dynamic analysis of sandwich beams with soft core was presented in Ref. [26]. The transverse shear stress field was assumed to follow a quadratic distribution in thick face layers and a uniform distribution in soft core. In this formulation, interlaminar continuity conditions of displacement and transverse shear stress were satisfied simultaneously, and transverse shear and cross-sectional warping effects in thick face layers were taken into account. A completely different idea to overcome the inaccuracy of FSDT was presented in Ref. [27]. The authors proposed transforming the through-thickness stress variations obtained from FSDT analysis into 3D elastic solutions using a surrogate model based on Gaussian regression. The surrogate model was then used to predict the through-thickness variations of the normal stresses. The proposed methodology is capable of capturing through-thickness stress variations equivalent to 3D elastic solutions. An interesting comparison of displacements determined using selected equivalent single-layer models of laminated plates with a 3D elastic solution was presented by Kreja and Sabik [28]. This comparison is an excellent illustration of the importance of the shear correction factor.

It should also be noted that several refined shear deformation theories have been developed to reduce or eliminate the need for an explicit shear correction factor. These include higher-order, layer-wise, zig-zag, and improved integral shear deformation theories, in which the through-thickness variation of displacements or stresses is represented more accurately than in classical FSDT. Recent examples include improved first-order or higher-order formulations for functionally graded and sandwich-type structures, where transverse shear effects are embedded in enriched kinematics rather than introduced through an external correction factor [29]. Such theories are especially valuable when local through-thickness stresses, vibration modes, or thickness-stretching effects are of primary interest. The present work follows a different but complementary route: it retains the simplicity and broad availability of FSDT/Mindlin–Reissner models and focuses on providing an energy-consistent shear stiffness calibration for geometrically complex sandwich cross-sections.

Existing approaches for determining shear correction factors in sandwich structures can therefore be broadly divided into analytical layered models, refined shear deformation theories, and fully numerical methods [30–32]. Layered analytical formulations are efficient and transparent, but they usually rely on assumed through-thickness shear-stress distributions and equivalent material properties. Refined theories provide richer kinematics, but they are less directly compatible with standard engineering FSDT implementations. Fully numerical approaches, such as three-dimensional finite element analyses, can resolve local interactions between corrugated facings and the core, but they are computationally demanding and less convenient for parametric studies or routine design. As a result, there remains a need for a method that bridges the gap between idealized layered theories and fully resolved numerical models while preserving physical transparency, computational efficiency, and direct compatibility with standard plate and shell formulations.

In this study, an energy-based framework is proposed for determining the shear correction factor in sandwich plates with flat or corrugated facings, including configurations in which the corrugation ribs are filled with soft core material. The formulation is based on strain-energy equivalence and explicitly relates the FSDT shear stiffness to the non-uniform distribution of transverse shear energy over the cross-section. First, a closed-form layered solution is developed for classical

three-layer sandwich plates and used as an analytical baseline. Subsequently, the method is generalized through a pixel-based formulation of the cross-section, which allows corrugated configurations with soft core fully occupying the profiled regions between the facings to be treated without reducing them to one-dimensional layer functions.

The main novelty of the paper is the extension of energy-consistent shear correction identification to corrugated sandwich cross-sections with spatially complex material layouts. In contrast to classical layered formulas, the proposed pixel-based formulation evaluates the shear energy directly from a resolved material map of the cross-section. In contrast to full three-dimensional finite element modelling, it does not require solving a boundary-value problem and can therefore be used efficiently in parametric studies and reduced-order modelling.

The main contributions of the paper are: (i) a closed-form energy-consistent shear correction factor for layered sandwich plates with homogenizable facings, (ii) a pixel-based generalization for corrugated cross-sections in which the soft core fully occupies the profiled regions between the facings, (iii) a comparison with EI-equivalent flat three-layer surrogates, and (iv) a discussion of the applicability and limitations of different reduced representations. The proposed approach is intended for direct use in Mindlin–Reissner plate and shell models, where it provides a physically grounded scaling of the transverse shear stiffness.

2. Materials and methods

This section presents a generalized analytical framework for determining the transverse shear correction factor of sandwich plates composed of a soft core and thin metal facings, one or both of which are corrugated. The formulation builds on the general concept of strain-energy equivalence used in heterogeneous and layered media, and extends it here to corrugated sandwich plates with pronounced stiffness contrast and geometrically induced anisotropy [33–39]. The method is fully compatible with first-order shear deformation theories and provides an effective shear correction factor suitable for plate- and shell-based numerical models.

2.1. Energy-based definition of the shear correction factor

The analyzed structure is a three-layer sandwich plate consisting of.

- a soft core of thickness h_c , characterized by a low shear modulus G_c ,
- one or two thin metallic facings of thickness $t_f \ll h_c$,
- optional geometric corrugation of the facings, introduced on one side (single-sided corrugation) or both sides (double-sided corrugation).

The global thickness of the reference corrugated configuration is

$$h = h_c + h_r + 2t_f \quad (1)$$

where h_c is the nominal core thickness, h_r is the corrugation height, and t_f is the facing thickness. For the EI-equivalent flat replacements considered later, two alternative geometric interpretations are used:

$$h = h_c + t_f + t_f^*, \quad (2a)$$

$$h = h_c^* + 2t_f \quad (2b)$$

where t_f^* denotes the thickness of an equivalent flat top facing in the first replacement, whereas h_c^* denotes the effective core thickness in the second replacement. These quantities are introduced only for the simplified flat surrogate models and should not be confused with the actual corrugated geometry shown in Fig. 1a and b. The corrugation is assumed to be periodic in the in-plane direction, with wavelength p and amplitude h_r . Its mechanical influence is incorporated through an equivalent stiffness description, without resolving local folding or contact effects.

The plate behavior is described using the first-order shear deformation theory (FSDT), where the displacement field is expressed as

$$u(x, y, z) = u_0(x, y) + z \theta_x(x, y), \quad (3a)$$

$$v(x, y, z) = v_0(x, y) + z \theta_y(x, y), \quad (3b)$$

$$w(x, y, z) = w_0(x, y), \quad (3c)$$

with u_0, v_0, w_0 denoting mid-surface displacements and θ_x, θ_y rotations of the normal.

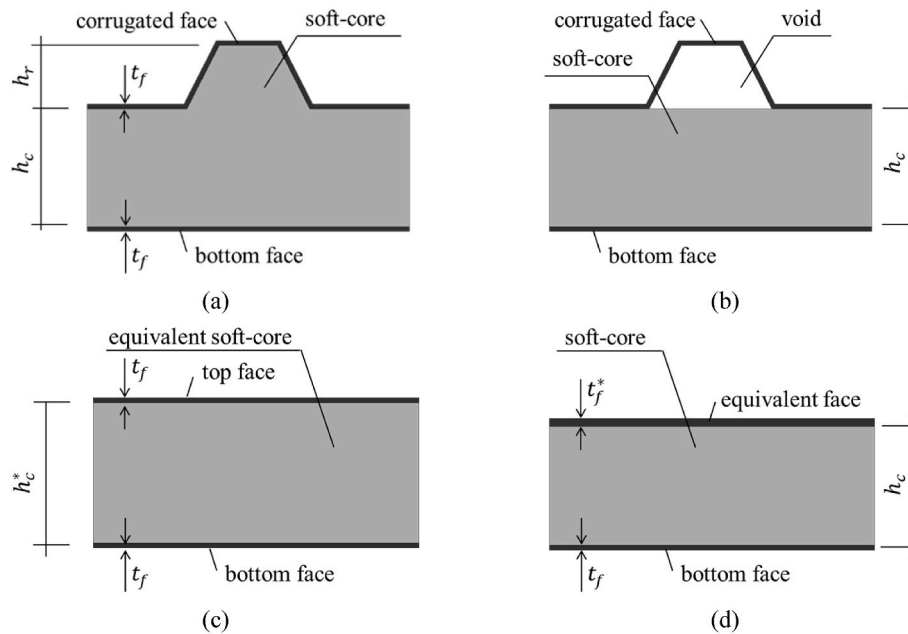


Fig. 1. Geometry and thickness definitions for corrugated sandwich configurations considered in the study. The overall thickness h is expressed in terms of the core thickness and facing thicknesses for (a)–(b) the reference corrugated configuration (Eq. (1)) and (c)–(d) for the EI-equivalent flat replacement (Eq. (2)).

The transverse shear strains are given by

$$\gamma_{xz} = \theta_x + \frac{\partial w_0}{\partial x} \quad (4a)$$

$$\gamma_{yz} = \theta_y + \frac{\partial w_0}{\partial y}. \quad (4b)$$

Due to the presence of a soft core and stiff facings, the shear strain distribution across the thickness is highly non-uniform, which necessitates the introduction of an appropriate shear correction factor. The present identification is formulated in terms of shear moduli G and does not explicitly involve Poisson's ratio; this is consistent with the FSDT shear-energy balance used here.

The exact transverse shear strain energy of the plate, per unit area, is defined as

$$U_s^{\text{exact}} = \frac{1}{2} \int_{-h/2}^{h/2} G(z) (\gamma_{xz}^2 + \gamma_{yz}^2) dz, \quad (5)$$

where $G(z)$ is the through-thickness distribution of the shear modulus.

For the sandwich plate, $G(z)$ is piecewise defined as

$$G(z) = \begin{cases} G_f^{\text{eq}}, & z \in \text{facing layers}, \\ G_c, & z \in \text{core}, \end{cases} \quad (6)$$

where G_f^{eq} is the equivalent shear modulus of the corrugated facing, discussed below.

The above formulation assumes that the shear modulus can be represented as a piecewise-defined function of the thickness coordinate. This description is fully adequate for sandwich plates with planar facings or corrugations that can be homogenized into an equivalent layer. In configurations where the core material completely fills the space between the corrugated facings (including the ribs), the notion of a single-valued function $G(z)$ becomes insufficient. In such cases, the present energy-based framework remains valid, but the stiffness field must be described in a more general spatial form, as introduced later in the pixel-based formulation.

The corrugated metallic facings are replaced by an energetically equivalent homogeneous layer. The equivalent shear modulus G_f^{eq} is obtained from the strain-energy equivalence condition

$$U_s^{\text{corr}} = U_s^{\text{eq}}, \quad (7)$$

where U_s^{corr} is the shear strain energy of the actual corrugated sheet over one period, and U_s^{eq} is the shear energy of a flat layer of thickness t_f .

The shear strain energy of the actual corrugated facing over one period p is expressed as

$$U_s^{\text{corr}} = \frac{1}{2} \int_0^p G_f \gamma_{\text{loc}}^2 t_f ds, \quad (8a)$$

where $ds = \sqrt{1 + (dz_c/dx)^2} dx$ is the differential arc-length of the corrugation profile, and γ_{loc} is the local shear strain component resolved along the tangent direction of the corrugated facing. Thus, γ_{loc} represents the shear deformation experienced by the inclined sheet segment, whereas γ_{xz} denotes the macroscopic transverse shear strain used in the equivalent flat representation.

The macroscopic transverse shear strain γ_{xz} is projected onto the local tangent direction, yielding

$$\gamma_{\text{loc}} = \gamma_{xz} \cos \theta = \frac{\gamma_{xz}}{\sqrt{1 + (dz_c/dx)^2}}, \quad (8b)$$

where θ is the local inclination angle of the corrugation profile. Substituting both the arc-length transformation and the projected strain into the energy expression gives

$$U_s^{\text{corr}} = \frac{1}{2} \int_0^p G_f \gamma_{xz}^2 t_f \frac{\sqrt{1 + (dz_c/dx)^2}}{1 + (dz_c/dx)^2} dx. \quad (8c)$$

For the energetically equivalent flat layer of thickness t_f , the shear strain energy over the same projected period reads

$$U_s^{\text{eq}} = \frac{1}{2} \int_0^p G_f^{\text{eq}} \gamma_{xz}^2 t_f dx. \quad (8d)$$

Enforcing the strain-energy equivalence condition $U_s^{\text{corr}} = U_s^{\text{eq}}$ over one corrugation period yields

$$G_f^{\text{eq}} = \frac{1}{p} \int_0^p \frac{G_f}{\sqrt{1 + (dz_c/dx)^2}} dx, \quad (8e)$$

where $z_c(x)$ describes the corrugation profile and G_f is the shear modulus of the base metal. Here, p denotes the corrugation wavelength. Equation (8) naturally accounts for the increased compliance induced by corrugation geometry and should be understood as an energy-equivalent homogenization of the corrugation-induced kinematic path length in the facing under transverse shear, suitable for reduced-order layered surrogates. Its role in the present work is to provide a consistent layered baseline; corrugated configurations in which the soft core fully occupies the profiled regions between the facings are addressed by the pixel-based identification, which does not rely on an equivalent-layer assumption.

The concept of an equivalent shear modulus is introduced here to account for the global compliance of corrugated facings under transverse shear. This representation is appropriate when the corrugation geometry can be energetically homogenized and treated as a distinct layer. However, when the profiled space formed by the corrugated facing is fully occupied by a soft-core material, local metal-core interaction may significantly affect the shear energy distribution. Such effects are not explicitly resolved at this level and are addressed in the pixel-based extension of the method presented in Section 2.2.

The shear correction factor is introduced through the equivalence between the exact transverse shear strain energy of the sandwich plate and the energy assumed in first-order shear deformation theory. For a unit-width plate subjected to a transverse shear force V , the exact shear strain energy is expressed as

$$U_s^{\text{exact}} = \frac{1}{2} V^2 \int_{-h/2}^{h/2} \frac{\phi(z)^2}{G(z)} dz, \quad (9)$$

where $G(z)$ is the local shear modulus and $\phi(z)$ is a normalized geometric shear form function describing the distribution of shear stress through the thickness. The function $\phi(z)$ depends solely on the cross-sectional geometry and satisfies the normalization condition

$$\int_{-h/2}^{h/2} \phi(z) dz = 1. \quad (10)$$

Within the framework of first-order shear deformation theory, the transverse shear strain energy is approximated as

$$U_s^{\text{FSDT}} = \frac{1}{2} \frac{V^2}{k_s G_{\text{ref}} h}. \quad (11)$$

Here, h is the total thickness of the panel, k_s is the shear correction factor, and G_{ref} is a reference shear modulus used to scale the transverse shear stiffness in the reduced FSDT model. The choice of G_{ref} is not unique; therefore, the numerical value of k_s must always be interpreted together with the adopted reference stiffness. In the layered formulation, G_{ref} is selected consistently with the one-dimensional through-thickness description. In the pixel-based formulation, $G_{\text{ref}} = G_{\text{eff}}$ is adopted, where G_{eff} is the area-weighted average shear modulus defined later in Eq.

(27). This convention provides a consistent scaling across all pixel-based cross-sections considered in the study. Equating Eqs. (9) and (11) yields the general energy-based definition of the shear correction factor

$$k_s = \frac{1}{G_{\text{ref}} h \int_{-h/2}^{h/2} \frac{\phi(z)^2}{G(z)} dz} \quad (12)$$

This expression highlights that the shear correction factor is governed not by an average shear modulus alone, but by the combined effect of the geometric shear distribution and the spatial variation of material stiffness. Equation (12) also shows the formal sensitivity of k_s to the selected reference modulus. If the same physical shear energy is represented using another reference modulus, the corresponding correction factor is rescaled according to $k_{s,\text{new}} G_{\text{ref,new}} = k_{s,\text{old}} G_{\text{ref,old}}$, provided that h and the underlying shear-energy integral remain unchanged. Thus, the physically meaningful quantity is the effective transverse shear stiffness $k_s G_{\text{ref}} h$, whereas the isolated numerical value of k_s is normalization-dependent. For this reason, all comparisons in this paper are performed under a fixed reference-modulus convention.

For a symmetric three-layer sandwich plate consisting of a soft core and two identical facings, the shear modulus distribution is defined piecewise as

$$G(z) = \begin{cases} G_c, & |z| \leq \frac{h_c}{2}, \\ G_f^{\text{eq}}, & \frac{h_c}{2} < |z| \leq \frac{h}{2}, \end{cases} \quad (13)$$

The shear correction factor k_s is defined through an energy equivalence between the exact shear energy and the FSDT representation (Eq. (12)). Since FSDT uses a single reference shear stiffness $G_{\text{ref}} h$, the numerical value of k_s depends on the adopted G_{ref} . In this study, G_{ref} is selected consistently with the geometric description: for layered models we use a thickness-based (layer-wise) reference consistent with Eq. (13), while for pixel-based cross-sections $G_{\text{ref}} = G_{\text{eff}}$ (Eq. (27)) is adopted, i.e., the area-weighted average shear modulus. With this convention, k_s becomes a geometry-sensitive scaling factor that can be directly used to correct the FSDT transverse shear stiffness $k_s G_{\text{ref}} A$. Importantly, all comparisons in Section 3 use the same G_{ref} convention, so differences in k_s reflect geometry and stiffness distribution rather than an arbitrary normalization.

For a rectangular cross-section of constant width, the geometric shear form function may be adopted in its classical parabolic form

$$\phi(z) = \frac{3}{2h} \left(1 - \left(\frac{2z}{h} \right)^2 \right), \quad (14)$$

This choice is retained here only for the layered closed-form baseline. It is consistent with classical FSDT practice and ensures recovery of the standard homogeneous rectangular-section limit. In this interpretation, the shape of $\phi(z)$ is driven by cross-sectional geometry, whereas material heterogeneity enters the energy balance through $G(z)$. For sandwich cross-sections with extreme stiffness contrast, however, the actual transverse shear stress distribution may deviate from the parabolic profile, particularly near the interfaces between stiff facings and a soft core. Therefore, the layered expression should be regarded as an analytical baseline for flat configurations or corrugated configurations that can be reasonably homogenized into equivalent layers, not as a complete description of local shear stresses. For corrugated configurations in which the soft core fully occupies the profiled regions between the facings, the pixel-based formulation introduced below is used to account for geometry-induced shear-energy localization at the cross-sectional level.

Substituting Eqs. (13) and (14) into the energy-based definition (12) leads to

$$k_s = \frac{1}{G_{\text{ref}} h \cdot 2 \left(\int_0^{h_c/2} \frac{\phi(z)^2}{G_c} dz + \int_{h_c/2}^{h/2} \frac{\phi(z)^2}{G_f^{\text{eq}}} dz \right)}. \quad (15)$$

Introducing the auxiliary function:

$$\Psi(z) = \frac{9}{4h^2} \left(z - \frac{8}{3} \frac{z^3}{h^2} + \frac{16}{5} \frac{z^5}{h^4} \right). \quad (16)$$

the integrals in Eq. (15) can be evaluated in closed form as

$$\int_a^b \phi(z)^2 dz = \Psi(b) - \Psi(a). \quad (17)$$

The resulting shear correction factor for the three-layer sandwich plate becomes

$$k_s = \frac{1}{G_{\text{ref}} h \cdot 2 \left(\frac{\Psi(h_c/2)}{G_c} + \frac{\Psi(h/2) - \Psi(h_c/2)}{G_f^{\text{eq}}} \right)}. \quad (18)$$

Unlike simplified averaging approaches, this formulation preserves the non-uniform shear energy distribution across the thickness and naturally converges to the classical value only in the homogeneous limit. Moreover, the structure of Eq. (18) is fully consistent with the pixel-based formulation introduced in the subsequent sections, where the continuous integrals are replaced by discrete summations over spatially varying material regions.

The derived shear correction factor k_s is directly applicable in:

- Mindlin–Reissner plate elements,
- layered shell elements with reduced integration,
- homogenized sandwich models using ABD stiffness matrices.

No modification of the constitutive formulation is required; only the transverse shear stiffness terms are scaled by the computed k_s .

It should be emphasized that the shear correction factor used in numerical plate or shell models may be obtained using different levels of geometric description. For sandwich plates with flat or effectively homogenized facings, the layered analytical expressions derived above provide a closed-form and computationally efficient solution. For corrugated configurations in which the soft core fully fills the profiled regions formed by the facings, the same energy-equivalence principle can be applied using a pixel-based description of the cross-section, as developed in the following sections.

2.2. Pixel-based shear correction factor

When corrugated or indented facings are tightly filled with a soft-core material (e.g., polymeric or mineral foam), the assumption of clearly separated layers with piecewise-constant shear moduli becomes questionable. In such configurations, the transverse shear stress is transferred through a geometrically complex region in which the soft core fully occupies the profiled space formed by the corrugated facings. The presented approach can be effectively applied to the analysis of sandwich panels made of various facing materials [39], taking into account the frequently observed variability of core properties [40].

It is important to distinguish the present pixel-based formulation from a standard finite element discretization. The cross-section is discretized into pixels only to perform numerical quadrature of the shear-energy expression over a spatially resolved material map. No nodal degrees of freedom, element shape functions, stiffness matrix assembly, boundary conditions, or global equilibrium equations are introduced at the pixel level. In a finite element model, convergence depends on interpolation order, mesh quality, boundary conditions, and the numerical solution of a boundary-value problem. In the present formulation, convergence is associated with the refinement of the cross-

sectional quadrature grid and with the ability of this grid to resolve the corrugation geometry and material interfaces.

In the numerical examples, the cross-section was discretized using a uniform pixel size of $\Delta x = \Delta z = 0.1$ mm. The same resolution was used for all analyzed geometries to ensure that the observed trends in k_s were not affected by changes in discretization density. Since the method is based on pixel-wise quadrature of the shear-energy expression, further grid refinement is expected to lead to convergent values once the corrugation folds and material interfaces are sufficiently resolved. As a consequence:

- the shear modulus $G(z)$ is no longer a single-valued function of the thickness coordinate,
- local shear deformation paths depend on the actual geometry of corrugation and filling,
- simplified equivalent-layer approaches may either overestimate or underestimate the effective shear stiffness.

To overcome these limitations, a pixel-based (voxel-based in 3D) strain-energy formulation is introduced, extending the continuous approach of Sections 2.1 to arbitrary corrugated geometries.

The sandwich plate cross-section is discretized into a regular grid of pixels (or voxels), each representing a small material region with constant properties. Each pixel is characterized by.

- a material indicator

$$\chi_{ij} = \begin{cases} 1 & \text{solid material (metal or core),} \\ 0 & \text{void,} \end{cases} \quad (19)$$

- a local shear modulus

$$G_{ij} = \begin{cases} G_f & \text{metallic facing,} \\ G_c & \text{core material,} \end{cases} \quad (20)$$

- pixel dimensions $\Delta x \times \Delta z$.

The cross-section is discretized into $N_x \times N_z$ cells. Index $i = 1, \dots, N_x$ denotes the column along the in-plane direction x , and $j = 1, \dots, N_z$ denotes the row along the thickness direction z . Each cell (i, j) has width Δx and height Δz , with $\chi_{ij} \in \{0, 1\}$ indicating void/solid and G_{ij} taking the material shear modulus of the phase occupying the cell.

This representation naturally captures.

- corrugation geometry,
- local metal–foam interaction,
- asymmetric or unilateral folding patterns.

The transverse shear force V is assumed to act globally on the cross-section. The geometric shear-stress form function is computed row-wise, independently of material stiffness, following equilibrium requirements.

For a horizontal pixel row j , the effective row width is

$$b_j = \sum_i \chi_{ij} \Delta x, \quad (21)$$

and the first moment of area above row j is

$$Q_j = \sum_{k \geq j} b_k (z_k - \bar{z}) \Delta z, \quad (22)$$

where $\bar{z}$ denotes the coordinate of the geometric centroid of the solid cross-section, computed from the pixel discretization over all material cells and consistent with the area definition used in the shear-energy formulation.

The normalized shear form function is then defined as

$$\phi_j = \frac{Q_j}{I b_j}, \quad (23)$$

with the second moment of area

$$I = \sum_{ij} \chi_{ij} (z_j - \bar{z})^2 \Delta x \Delta z. \quad (24)$$

Importantly, ϕ_j depends only on geometry, not on material properties, and is therefore consistent with classical beam and plate theory.

The exact transverse shear strain energy per unit plate area is computed by summing the local energy contributions of all pixels:

$$U_s^{\text{pix}} = \frac{1}{2} V^2 \sum_{ij} \chi_{ij} \frac{\phi_j^2}{G_{ij}} \Delta x \Delta z. \quad (25)$$

This expression generalizes Eq. (5) and remains valid regardless of.

- corrugation depth,
- fold inclination,
- degree of core filling within the profiled regions.

The shear correction factor is obtained by enforcing equivalence between the pixel-based shear energy (25) and the FSDT shear energy (11). This yields

$$k_s^{\text{pix}} = \frac{1}{G_{\text{eff}} A \sum_{ij} \chi_{ij} \frac{\phi_j^2}{G_{ij}} \Delta x \Delta z}, \quad (26)$$

where.

- $A = \sum_{ij} \chi_{ij} \Delta x \Delta z$ is the total solid area,
- in the pixel-based formulation, the effective shear modulus G_{eff} is defined as the area-weighted average of the local shear moduli, i.e.

$$G_{\text{eff}} = \frac{1}{A} \sum_{ij} \chi_{ij} G_{ij} \Delta x \Delta z. \quad (27)$$

Equation (26) is the most general form of the shear correction factor in the present study. Because k_s is defined relative to the adopted FSDT reference stiffness, its absolute magnitude is not intended to reproduce classical constants (e.g., 5/6) unless the same reference convention is used. Here, k_s is reported as a geometry-sensitive scaling coefficient that enables consistent stiffness correction within the same G_{ref} definition; therefore, comparisons across cases are performed exclusively under an unchanged G_{ref} convention.

The dependence of k_s on the reference modulus can be interpreted directly from Eq. (26). If G_{eff} is replaced by another admissible reference modulus, for example the core modulus G_c or a selected layer-wise average, the numerical value of k_s changes in inverse proportion to that modulus. However, the product $k_s G_{\text{eff}} A$, which defines the effective transverse shear stiffness used in the FSDT model, remains the relevant energy-consistent quantity. This distinction is particularly important for the present sandwich cross-sections, where the stiff metallic facings may dominate the area-weighted reference modulus, whereas the actual shear compliance is governed mainly by the soft core.

An essential requirement for any generalized shear correction framework is its consistency with classical theories in appropriate limiting cases. The pixel-based formulation proposed in this study satisfies this requirement in a natural and physically transparent manner. When the corrugation amplitude of the facings tends to zero and the geometry approaches that of planar layers, the spatial distribution of material properties becomes effectively one-dimensional along the thickness coordinate. In this limit, the local shear modulus G_{ij} varies only with the thickness coordinate z , and the pixel-based shear energy expression in Eq. (25) reduces to the continuous layered formulation introduced in Section 2.1. Consequently, the shear correction factor

given by Eq. (26) converges exactly to the energy-based layered expression defined in Eq. (12), demonstrating full consistency with classical sandwich plate theory.

A second important limiting case corresponds to a homogeneous plate, where the shear modulus is constant throughout the cross-section. In this situation, the local stiffness contrast vanishes, and the pixel-based summation simplifies, as $G_{ij} = \text{const}$ can be factored out of the energy expression. The resulting shear correction factor is then governed solely by the geometric shear form function and recovers the well-known classical value for a rectangular cross-section. This confirms that the proposed formulation does not introduce artificial corrections in cases where traditional assumptions remain valid. This limiting behavior was additionally used as an internal verification of the implementation: for a flat three-layer sandwich discretized by the same pixel procedure, the value of k_s converges to the closed-form layered expression given by Eq. (18) as the pixel size is refined.

Of particular relevance to corrugated sandwich plates is the limit of a strongly compliant core material, for which the shear modulus of the filling is orders of magnitude lower than that of the metallic facings. In this regime, the transverse shear strain energy localizes predominantly within the core material occupying the corrugation valleys and interfacial regions. The pixel-based formulation captures this effect automatically through the local weighting by ϕ_j^2/G_{ij} in the pixel-wise energy sum (Eq. (25)), without the need for predefined shear shape functions or empirical correction factors. As a result, the effective shear correction factor reflects the actual load-transfer mechanism dictated by the combined geometry of corrugation and core filling, rather than an idealized layered description.

From a practical perspective, the pixel-based approach provides a robust extension of classical shear correction concepts to sandwich plates with geometrically complex facings and fully bonded soft cores. Its main advantage lies in the explicit separation between geometry and material properties: the geometric shear form function depends solely on the shape of the cross-section, while material heterogeneity enters only through the local shear modulus field. In both the layered and pixel-based formulations, the transverse shear stiffness is consistently scaled using the same reference shear modulus G_{ref} , ensuring a unified energetic interpretation across different levels of geometric description. This structure allows the method to accommodate arbitrary corrugation profiles, asymmetric folding, and partial or complete filling of the corrugated region, all within a single unified framework.

Although the formulation is expressed in discrete form, it does not rely on finite element shape functions or numerical solution of boundary value problems. Instead, the shear correction factor is obtained directly from an energy balance evaluated through pixel-wise quadrature. This makes the method computationally efficient and particularly attractive for parametric studies, optimization of corrugation geometries, or sensitivity analyses with respect to material contrast and filling ratios. At the same time, the resulting correction factor can be seamlessly integrated into conventional Mindlin–Reissner plate or shell models, preserving compatibility with standard engineering workflows.

It is important to emphasize that the pixel-based formulation should be viewed as a generalization rather than a replacement of classical layered approaches. For sandwich plates with flat facings and well-defined layer boundaries, the simpler layered expressions remain sufficient and computationally optimal. However, when the soft core fully occupies the profiled regions formed by the corrugated facings, the pixel-based method offers a physically grounded means of quantifying transverse shear effects that cannot be captured by equivalent-layer models alone. In this sense, the proposed approach provides a continuous methodological bridge between idealized sandwich theory and fully resolved microstructural descriptions, enabling accurate shear correction factors to be derived across a wide spectrum of practical sandwich configurations.

3. Results

3.1. Pixel-based reference results for all corrugated cross-sections

The proposed pixel-based framework was first applied to all corrugated cross-sections shown in Fig. 2(a–f) (variants 40–120 mm). The variant designation corresponds to the panel thickness without taking into account the ribs, i.e. it is $h_c + 2t_f$, see Fig. 1a. For each geometry, the method provides two global stiffness measures: the effective bending stiffness $(EI)_{\text{pix}}$ and the energy-consistent shear correction factor k_s^{pix} (or, equivalently, the effective transverse shear stiffness). The resulting set $\{(EI)_{\text{pix}}, k_s^{\text{pix}}\}$ for all analyzed geometries is summarized in Table 1 and is used as the reference dataset for the subsequent comparisons.

It is worth emphasizing that the resulting k_s values are of order 10^{-3} – 10^{-2} . These values should not be compared directly with the classical homogeneous-plate value of 5/6 without considering the reference stiffness used in the definition. In the present formulation, the FSDT shear term is written with a global reference stiffness $G_{\text{ref}}A$, with $G_{\text{ref}} = G_{\text{eff}}$ for the pixel-based model. Since G_{eff} is strongly influenced by the stiff metallic facings, while the actual shear deformation energy is concentrated mainly in the soft core occupying the profiled regions formed by the corrugated facings, the energy-consistent correction factor must significantly reduce the reference stiffness. Thus, small k_s values are a physical indication of a core-dominated shear mechanism and shear-energy localization in compliant regions, rather than a numerical anomaly.

The obtained values show a systematic dependence on the edge geometry and on the spatial arrangement of the soft core within the corrugated cross-section. Since the pixel-based model explicitly resolves the geometric details, these results represent the most resolved description within the present cross-section-based framework. Accordingly, the term “reference” is used here in a method-internal sense: the pixel-based cross-section is the most resolved representation considered in this study, but it is not claimed to replace an experimentally validated or fully three-dimensional elasticity solution. At the same time, for practical modeling purposes, it is important to establish whether an equivalent layered model can reproduce the same global response, while replacing the complex geometry by a standard flat three-layer sandwich.

3.2. Construction of an EI-equivalent flat three-layer model with fixed facings

To investigate the validity of a simplified representation, an equivalent flat three-layer sandwich is introduced. In this reduction, the facing thickness t_f is kept fixed, reflecting typical manufacturing constraints, while the effective core thickness h_c^* is identified such that the bending stiffness of the flat model matches the pixel-based reference value:

$$(EI)_{\text{flat}}(h_c^*) = (EI)_{\text{pix}}. \quad (28)$$

For a symmetric sandwich beam of unit width, composed of two facings of thickness t_f and Young's modulus E_f , and a core of thickness h_c^* with Young's modulus E_c , the bending stiffness is written as

$$(EI)_{\text{flat}} = 2E_f \left[\frac{t_f^3}{12} + t_f \left(\frac{h_c^*}{2} + \frac{t_f}{2} \right)^2 \right] + E_c \frac{(h_c^*)^3}{12}. \quad (29)$$

After expansion, Eq. (29) becomes a cubic polynomial in h_c^* ,

$$(EI)_{\text{flat}} = \frac{E_c}{12} (h_c^*)^3 + \frac{E_f t_f}{2} (h_c^*)^2 + E_f t_f^2 h_c^* + \frac{2}{3} E_f t_f^3. \quad (30)$$

Imposing Eq. (28) yields

$$\frac{E_c}{12} (h_c^*)^3 + \frac{E_f t_f}{2} (h_c^*)^2 + E_f t_f^2 h_c^* + \frac{2}{3} E_f t_f^3 - (EI)_{\text{pix}} = 0, \quad (31)$$

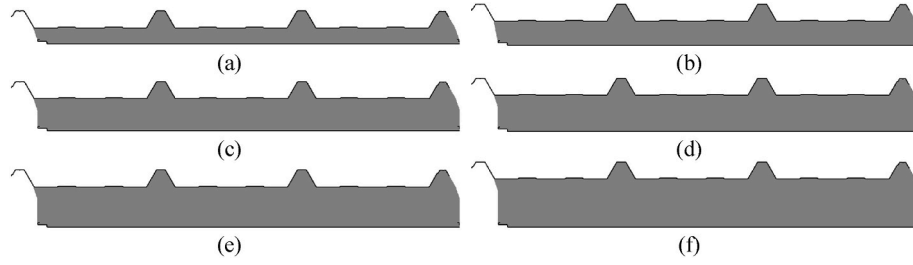


Fig. 2. Investigated corrugated sandwich cross-sections used in the pixel-based analysis: panel type (a) 40 mm, (b) 60 mm, (c) 80 mm, (d) 90 mm, (e) 100 mm, and (f) 120 mm.

Table 1

Pixel-based reference results for all investigated cross-sections: effective bending stiffness $(EI)_{\text{pix}}$ and shear correction factor k_s^{pix} .

Panel type	$t_f = 1.0 \text{ mm}$		$t_f = 1.5 \text{ mm}$		$t_f = 2.0 \text{ mm}$	
	$(EI)_{\text{pix}}$	k_s^{pix}	$(EI)_{\text{pix}}$	k_s^{pix}	$(EI)_{\text{pix}}$	k_s^{pix}
	[Nmm ²]	[–]	[Nmm ²]	[–]	[Nmm ²]	[–]
40	4.809E+11	3.610E-03	7.311E+11	2.531E-03	9.882E+11	1.992E-03
60	8.363E+11	5.951E-03	1.266E+12	4.096E-03	1.705E+12	3.165E-03
80	1.304E+12	8.162E-03	1.969E+12	5.563E-03	2.645E+12	4.258E-03
90	1.580E+12	9.181E-03	2.384E+12	6.241E-03	3.199E+12	4.763E-03
100	1.884E+12	1.015E-02	2.840E+12	6.889E-03	3.808E+12	5.247E-03
120	2.577E+12	1.200E-02	3.879E+12	8.125E-03	5.193E+12	6.172E-03

and the physically admissible solution is selected as the positive real root.

All results reported below were obtained for corrugated sandwich cross-sections of real width $b = 1280 \text{ mm}$. The material parameters used in the study were steel facings with shear modulus $G_f = 80 \text{ GPa}$ and a soft core with shear modulus $G_c = 20 \text{ MPa}$. These values were used consistently in both the pixel-based and flat equivalent representations. In the following, h_c^* denotes the effective core thickness of the EI-equivalent flat model, whereas G_c^* denotes the adjusted core shear modulus used when shear-stiffness equivalence is imposed. These starred quantities are parameters of the simplified flat surrogate and do not represent directly measured material or geometric properties of the corrugated panel.

For each corrugated cross-section, the bending stiffness $(EI)_{\text{pix}}$ was computed directly from the pixel-resolved geometry using the full solid area and the actual width b . A flat three-layer cross-section of the same width b and identical facing thickness t_f was then introduced. The effective core thickness h_c^* was identified from the bending equivalence condition in Eq. (28).

Since the identification of h_c^* modifies the total solid area A^* of the flat section, a direct comparison of transverse shear stiffness would include an artificial area effect. To eliminate this influence, shear-stiffness equivalence was enforced in the form

$$G_{\text{eff}}^* A^* = G_{\text{eff}} A, \quad (32)$$

The shear correction factor k_s was then computed for both representations using a consistent normalization, with $G_{\text{ref}} = G_{\text{eff}}$ for the pixel-based cross-section and $G_{\text{ref}} = G_{\text{eff}}^*$ for the flat equivalent model. With this convention, differences in k_s reflect differences in shear kinematics and stiffness distribution rather than normalization effects.

The resulting h_c^* values for all cross-sections are reported in Table 2. The trends of h_c^* and the corresponding $G_c^* = G_c h_c / h_c^*$ are illustrated in Fig. 3.

3.3. Global deflections: pixel model versus EI-equivalent flat model

To compare the influence of geometric simplification on the global response, a simply supported beam-type strip benchmark (unit-width/

Table 2

Parameters of the EI-equivalent flat layered model with fixed facing thickness t_f : identified effective core thickness h_c^* (from the EI-calibration) and the corresponding effective core shear modulus G_c^* used in the flat shear term.

Panel type	$t_f = 1.0 \text{ mm}$		$t_f = 1.5 \text{ mm}$		$t_f = 2.0 \text{ mm}$	
	h_c^*	G_c^*	h_c^*	G_c^*	h_c^*	G_c^*
	[mm]	[MPa]	[mm]	[MPa]	[mm]	[MPa]
40	58.747	15.248	58.670	15.269	58.589	15.265
60	77.762	16.320	77.662	16.341	77.576	16.333
80	97.313	16.875	97.201	16.895	97.099	16.880
90	107.198	17.068	107.092	17.085	106.974	17.075
100	117.126	17.209	117.008	17.226	116.885	17.218
120	137.100	17.426	136.964	17.443	136.806	17.429

plate-strip idealization) of span $L = 3000 \text{ mm}$ and width $b = 1280 \text{ mm}$ is considered. The strip is subjected to a centrally applied transverse load $P = 1000 \text{ N}$. For clarity and direct comparison of bending and transverse shear effects, the response is evaluated using a one-dimensional formulation in the longitudinal direction, consistent with plate-strip bending, without introducing Poisson ratio effects. This benchmark is intentionally one-dimensional and is used only to isolate the relative bending vs. shear contributions under a consistent G_{ref} convention.

The mid-span deflection is decomposed into bending and shear contributions,

$$w = w_b + w_s = \frac{PL^3}{48(EI)} + \frac{PL}{4 k_s G_{\text{ref}} A}. \quad (33)$$

Here, (EI) denotes the bending stiffness of the considered cross-section over the full width b , A is the total solid cross-sectional area, and G_{ref} is the reference shear modulus adopted in the shear correction procedure.

Pixel-based model. For each corrugated cross-section, the pixel procedure provides $(EI)_{\text{pix}}$ and k_s^{pix} . The associated shear reference stiffness is taken as $G_{\text{ref}} = G_{\text{eff}}$, where G_{eff} is the area-weighted average shear modulus defined in Eq. (27). The total solid area is

$$A = A_f + A_c, \quad (34)$$

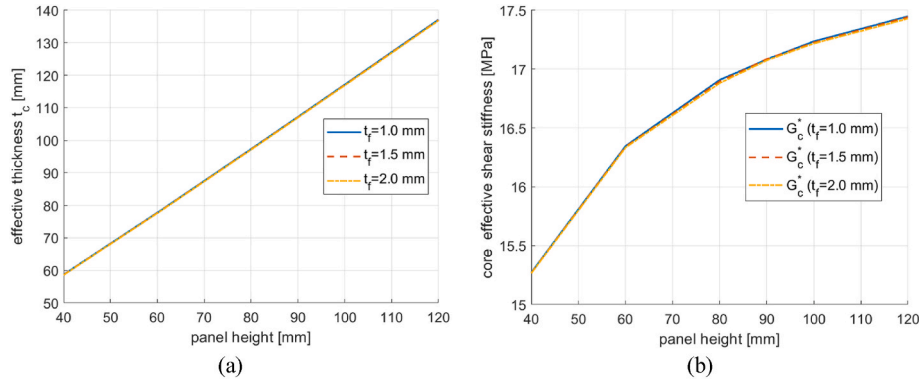


Fig. 3. EI-equivalent flat-model parameters for all panel types: (a) identified effective core thickness h_c^* ; (b) corresponding effective core shear modulus G_c^* .

where A_f and A_c are the areas of facings and core, respectively, extracted directly from the pixel grid (via χ_{ij}). The mid-span deflection prediction reads

$$w_{\text{pix}} = \frac{PL^3}{48(EI)_{\text{pix}}} + \frac{PL}{4k_s^{\text{pix}} G_{\text{eff}} A}. \quad (35)$$

EI-equivalent flat model. The equivalent flat three-layer cross-section is constructed with the same facing thickness t_f and unit width b , while the effective core thickness h_c^* is identified from the bending equivalence condition in Eq. (28). This changes the total solid area of the flat section to

$$A^* = A_f + A_c^*, A_c^* = b h_c^*, \quad (36)$$

and thus would artificially modify the shear stiffness if the same material parameters were used directly. To isolate the effect of shear kinematics (captured by k_s) from a trivial change of area, we enforce the shear-stiffness equivalence between the pixel section and its flat replacement according to Eq. (32), which gives

$$G_{\text{eff}}^* = G_{\text{eff}} \frac{A}{A^*}. \quad (37)$$

With this convention, the flat model uses the same global reference shear stiffness $G_{\text{eff}} A$ as the pixel model, and any remaining difference in the shear term is attributable to the identified correction factor k_s , not to the area scaling. The flat-model deflection is therefore computed as

$$w_{\text{flat}} = \frac{PL^3}{48(EI)_{\text{flat}}} + \frac{PL}{4k_s^{\text{flat}} G_{\text{eff}}^* A^*}, \quad (38)$$

where k_s^{flat} is obtained by applying the same energy-consistent identification procedure as for the pixel model, but to the flat three-layer cross-section. This notation is used consistently in all subsequent tables and figures: quantities marked by an asterisk refer to the EI-equivalent flat surrogate, while quantities marked by the superscripts pix and flat refer to the pixel-based corrugated cross-section and the calibrated flat model, respectively.

Table 3

Effective stiffness measures and shear correction factors for the EI-equivalent flat model: $(EI)_{\text{flat}}$ and k_s^{flat} reported for each panel height and facing thickness t_f .

Panel type	$t_f = 1.0$ mm		$t_f = 1.5$ mm		$t_f = 2.0$ mm	
	$(EI)_{\text{flat}}$	k_s^{flat}	$(EI)_{\text{flat}}$	k_s^{flat}	$(EI)_{\text{flat}}$	k_s^{flat}
	[Nmm ²]	[–]	[Nmm ²]	[–]	[Nmm ²]	[–]
40	4.316E+11	4.661E-03	9.835E+11	3.115E-03	1.767E+12	2.334E-03
60	7.613E+11	6.579E-03	1.719E+12	4.390E-03	3.048E+12	3.276E-03
80	1.184E+12	8.441E-03	2.705E+12	5.676E-03	4.818E+12	4.250E-03
90	1.444E+12	9.407E-03	3.281E+12	6.314E-03	5.855E+12	4.736E-03
100	1.731E+12	1.036E-02	3.914E+12	6.944E-03	6.993E+12	5.216E-03
120	2.381E+12	1.225E-02	5.347E+12	8.199E-03	9.573E+12	6.170E-03

This beam-type benchmark is used solely to compare the global compliance decomposition (bending vs. shear) and to assess whether the EI-equivalent layered replacement reproduces the shear-correction trends of the fully resolved pixel geometry. The benchmark does not aim to replace a full plate model; rather, it provides a transparent, unit-width comparison that isolates the impact of k_s on the global response.

The resulting values of k_s^{flat} and the corresponding effective bending stiffnesses are summarized in Table 3 and compared to the pixel-based values in Fig. 4 for all analyzed cross-sections.

Fig. 4 shows that the EI-equivalent flat model follows the pixel-based

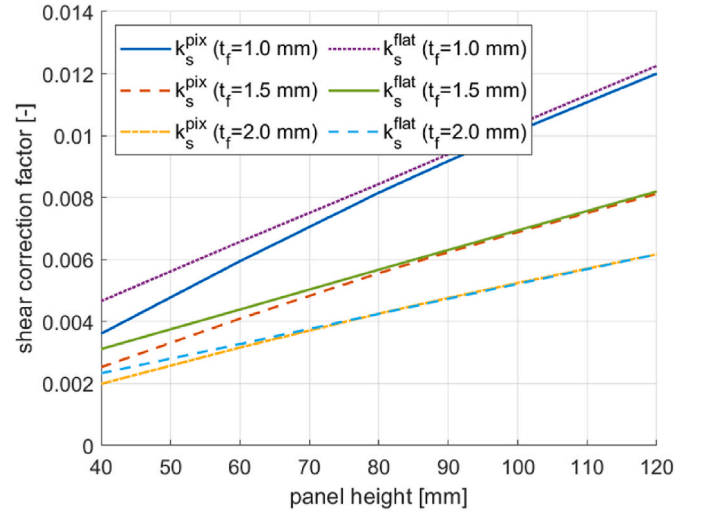


Fig. 4. Comparison of the identified shear correction factors for the corrugated sandwich cross-sections and their EI-equivalent flat replacements: k_s^{pix} obtained from the pixel-based model (Table 1) versus k_s^{flat} computed for the calibrated three-layer flat model (Table 3), shown as functions of panel type for three facing thicknesses $t_f = 1.0, 1.5$, and 2.0 mm.

k_s trends for all investigated facing thicknesses. This agreement indicates that, after enforcing bending equivalence and using a consistent reference shear stiffness, the dominant part of the transverse shear correction is governed by the effective through-thickness stiffness distribution. The remaining deviations between k_s^{pix} and k_s^{flat} reflect the influence of explicitly resolved corrugation geometry and the local distribution of the soft core within the profiled regions formed by the facings, which cannot be fully represented by a one-dimensional flat surrogate. Therefore, Fig. 4 should be interpreted as a comparison between two reduced-order descriptions rather than as an independent validation against a full three-dimensional solution.

3.4. Engineering baseline: core-only shear with $k_{s,56} = 5/6$ (pixel model)

Finally, a common engineering baseline is introduced by replacing the identified correction factor by the classical value

$$k_{s,56} = \frac{5}{6}. \quad (39)$$

To provide a meaningful reference point, a simplified baseline model frequently encountered in engineering practice is introduced. In this approximation, the transverse shear deformation is assumed to be carried exclusively by the core, while the facings contribute only to bending stiffness. This assumption effectively neglects any shear participation of the corrugated facings and replaces the detailed shear-stiffness identification by a core-only contribution.

Such a formulation is not intended to validate the equivalent-layer model developed above. Rather, it serves as a controlled comparison, allowing the deviation introduced by this widespread simplification to be quantified explicitly.

Under this assumption, the mid-span deflection of a simply supported beam subjected to a central point load P can be expressed as

$$w_{\text{pix}}^* = \frac{PL^3}{48(EI)_{\text{pix}}} + \frac{PL}{4k_{s,56}G_cA_c}, \quad (40)$$

where A_c is the core area extracted from the pixel cross-section and G_c is the core shear modulus.

Flat-model core-only baseline. The corresponding baseline for the EI-equivalent flat section reads

$$w_{\text{flat}}^* = \frac{PL^3}{48(EI)_{\text{flat}}} + \frac{PL}{4k_{s,56}G_c^*A_c^*}, \quad (41)$$

where A_c^* is defined in Eq. (36) and G_c^* is chosen to preserve the core-only shear stiffness, $G_c^*A_c^* = G_cA_c$.

Under this definition, the shear term in Eqs. (40) and (41) becomes identical by construction, and any residual differences between w_{pix}^* and w_{flat}^* are attributable to numerical tolerance in the EI-calibration (i.e., $(EI)_{\text{flat}} \approx (EI)_{\text{pix}}$) rather than to shear modeling.

The core-only baseline therefore provides a clear reference level against which the energy-consistent predictions (Eqs. (35) and (38), using k_s^{pix} and k_s^{flat}) can be compared. In particular, deviations between

the baseline and energy-consistent shear deflections quantify when the classical assumption $k_s = 5/6$ with core-only shear is acceptable and when it becomes unreliable for corrugated, stiffness-heterogeneous sandwich cross-sections.

The mid-span deflections obtained for the reference loading case ($L = 3000$ mm, $P = 1000$ N, $b = 1280$ mm) are summarized in Tables 4–6 for the three considered facing thicknesses. For each panel height, the bending contribution w_b , the shear contribution w_s , and the benchmark shear deflection $w_{s,56}$ corresponding to $k_s = 5/6$ and core-only shear are reported for both the pixel-resolved cross-section and the EI-equivalent flat model.

As expected from the enforced shear-stiffness equivalence, the benchmark shear components $w_{s,56}^{\text{pix}}$ and $w_{s,56}^{\text{flat}}$ coincide, confirming internal consistency of the baseline comparison.

The total mid-span deflections $w = w_b + w_s$ as well as the benchmark totals $w^* = w_b + w_{s,56}$ are additionally compared in relative terms in Tables 7–9. This allows direct assessment of the influence of shear correction modeling and geometric simplification on the global compliance.

The trends observed in Tables 4–9 are summarized graphically in Fig. 5. The figure compares the bending and shear components, as well as total mid-span deflections obtained from the pixel-based cross-sections and their EI-equivalent flat counterparts for all considered panel heights and facing thicknesses. Both the energy-consistent shear correction results and the benchmark case based on $k_s = 5/6$ with core-only shear are included.

This graphical comparison highlights the relative contribution of transverse shear to the overall compliance and allows direct assessment of the deviation introduced by geometric simplification and classical shear correction assumptions.

4. Discussion

The pixel-based reference results (Table 1) confirm that both the

Table 5

Mid-span deflection components for $t_f = 1.5$ mm: bending contribution w_b , shear contribution w_s , and benchmark shear deflection $w_{s,56}$ computed using $k_s = 5/6$, reported for both pixel-based and flat models.

Panel type	w_b^{pix} [mm]	w_b^{flat} [mm]	w_s^{pix} [mm]	w_s^{flat} [mm]	$w_{s,56}^{\text{pix}}$ [mm]	$w_{s,56}^{\text{flat}}$ [mm]
40	7.694E-01	5.719E-01	8.821E-01	8.618E-01	7.849E-01	7.849E-01
60	4.443E-01	3.272E-01	5.443E-01	6.264E-01	5.541E-01	5.541E-01
80	2.857E-01	2.079E-01	4.003E-01	4.920E-01	4.282E-01	4.282E-01
90	2.359E-01	1.714E-01	3.563E-01	4.447E-01	3.843E-01	3.843E-01
100	1.981E-01	1.437E-01	3.227E-01	4.052E-01	3.488E-01	3.488E-01
120	1.450E-01	1.052E-01	2.732E-01	3.445E-01	2.943E-01	2.943E-01

Table 4

Mid-span deflection components for $t_f = 1.0$ mm: bending contribution w_b , shear contribution w_s , and benchmark shear deflection $w_{s,56}$ computed using $k_s = 5/6$, reported for both pixel-based and flat models.

Panel type	w_b^{pix} [mm]	w_b^{flat} [mm]	w_s^{pix} [mm]	w_s^{flat} [mm]	$w_{s,56}^{\text{pix}}$ [mm]	$w_{s,56}^{\text{flat}}$ [mm]
40	1.170E+00	1.303E+00	9.250E-01	7.229E-01	7.837E-01	7.837E-01
60	6.726E-01	7.389E-01	5.599E-01	5.213E-01	5.532E-01	5.532E-01
80	4.314E-01	4.751E-01	4.073E-01	4.080E-01	4.274E-01	4.274E-01
90	3.560E-01	3.895E-01	3.619E-01	3.683E-01	3.840E-01	3.840E-01
100	2.986E-01	3.250E-01	3.268E-01	3.350E-01	3.483E-01	3.483E-01
120	2.183E-01	2.362E-01	2.759E-01	2.846E-01	2.939E-01	2.939E-01

Table 6

Mid-span deflection components for $t_f = 2.0$ mm: bending contribution w_b , shear contribution w_s , and benchmark shear deflection $w_{s,56}$ computed using $k_s = 5/6$, reported for both pixel-based and flat models.

Panel type	w_b^{pix} [mm]	w_b^{flat} [mm]	w_s^{pix} [mm]	w_s^{flat} [mm]	$w_{s,56}^{\text{pix}}$ [mm]	$w_{s,56}^{\text{flat}}$ [mm]
40	5.692E-01	3.183E-01	8.423E-01	9.681E-01	7.862E-01	7.862E-01
60	3.299E-01	1.845E-01	5.296E-01	7.087E-01	5.549E-01	5.549E-01
80	2.127E-01	1.167E-01	3.934E-01	5.596E-01	4.290E-01	4.290E-01
90	1.758E-01	9.607E-02	3.513E-01	5.061E-01	3.849E-01	3.849E-01
100	1.477E-01	8.044E-02	3.188E-01	4.621E-01	3.494E-01	3.494E-01
120	1.083E-01	5.876E-02	2.708E-01	3.937E-01	2.949E-01	2.949E-01

effective bending stiffness $(EI)_{\text{pix}}$ and the identified shear correction factor k_s^{pix} vary systematically with the cross-section height h and with the facing thickness t_f . As expected, $(EI)_{\text{pix}}$ increases monotonically with h , reflecting the increasing lever arm of the facings and the resulting growth of global bending resistance. In parallel, k_s^{pix} also exhibits a consistent dependence on h , indicating that the transverse shear response evolves with the geometry and cannot be described by a universal constant independent of cross-sectional topology.

Table 7

Total mid-span deflections for $t_f = 1.0$ mm: w_{pix} , w_{flat} , and benchmark totals w_{pix}^* , w_{flat}^* obtained using $k_s = 5/6$ with core-only shear. Relative differences are reported with respect to the pixel-based reference solution.

Panel type	w_{pix} [mm]	w_{flat} [mm]	w_{pix}^* [mm]	w_{flat}^* [mm]	diff. w_{flat} [%]	diff. w_{pix}^* [%]	diff. w_{flat}^* [%]
40	2.0947	2.0262	1.9534	2.0870	-3.27%	-6.75%	-0.37%
60	1.2325	1.2602	1.2258	1.2920	2.25%	-0.54%	4.83%
80	0.8387	0.8831	0.8587	0.9024	5.29%	2.38%	7.60%
90	0.7179	0.7578	0.7400	0.7735	5.56%	3.08%	7.74%
100	0.6254	0.6600	0.6469	0.6733	5.53%	3.44%	7.66%
120	0.4942	0.5209	0.5122	0.5302	5.40%	3.64%	7.28%

Table 8

Total mid-span deflections for $t_f = 1.5$ mm, including pixel-based and flat-model predictions as well as benchmark totals computed with $k_s = 5/6$. The reported relative errors quantify the deviation of the flat and benchmark responses from the pixel-based solution.

Panel type	w_{pix} [mm]	w_{flat} [mm]	w_{pix}^* [mm]	w_{flat}^* [mm]	diff. w_{flat} [%]	diff. w_{pix}^* [%]	diff. w_{flat}^* [%]
40	1.6515	1.4337	1.5543	1.3569	-13.19%	-5.89%	-17.84%
60	0.9886	0.9536	0.9984	0.8813	-3.54%	0.99%	-10.85%
80	0.6860	0.7000	0.7138	0.6361	2.04%	4.05%	-7.27%
90	0.5922	0.6161	0.6202	0.5557	4.04%	4.73%	-6.16%
100	0.5208	0.5489	0.5469	0.4926	5.40%	5.01%	-5.41%
120	0.4182	0.4497	0.4393	0.3995	7.53%	5.05%	-4.47%

Table 9

Total mid-span deflections for $t_f = 2.0$ mm. The table compares pixel-based and EI-equivalent flat models for both energy-consistent shear correction and the classical $k_s = 5/6$ core-only baseline. Relative differences are given in percentage form.

Panel type	w_{pix} [mm]	w_{flat} [mm]	w_{pix}^* [mm]	w_{flat}^* [mm]	diff. w_{flat} [%]	diff. w_{pix}^* [%]	diff. w_{flat}^* [%]
40	1.4116	1.2864	1.3554	1.1045	-8.87%	-3.98%	-21.76%
60	0.8595	0.8932	0.8849	0.7395	3.92%	2.96%	-13.96%
80	0.6061	0.6763	0.6416	0.5457	11.58%	5.86%	-9.97%
90	0.5271	0.6022	0.5608	0.4810	14.25%	6.39%	-8.75%
100	0.4665	0.5425	0.4971	0.4298	16.29%	6.56%	-7.87%
120	0.3791	0.4524	0.4032	0.3536	19.34%	6.36%	-6.73%

The influence of facing thickness is similarly pronounced. At fixed h , thicker facings increase $(EI)_{\text{pix}}$ while reducing k_s^{pix} (Table 1). This trend suggests that stiffening the facings changes the relative contribution of transverse shear to the overall compliance and modifies the effective shear deformation pattern captured by the energy-consistent identification.

The EI-equivalent flat replacement provides a controlled setting to examine whether a simplified layered representation can reproduce the shear-correction trends observed in the pixel model. The identified effective core thickness h_c^* and the corresponding adjusted core shear modulus G_c^* (Table 2 and Fig. 3) evolve smoothly with h and t_f , reflecting the need to modify the effective separation and shear stiffness of the flat model so that it remains comparable to the corrugated reference. Importantly, after this calibration, the resulting k_s^{flat} closely follows k_s^{pix} across all cases (Table 3 and Fig. 4). The agreement indicates that once bending equivalence is enforced and the reference shear stiffness normalization is handled consistently, the shear correction factor is governed primarily by the effective stiffness distribution through the thickness rather than by the explicit corrugation details. From a reduced-order modeling perspective, this supports using an EI-calibrated three-layer surrogate to capture k_s trends in corrugated configurations while avoiding explicit geometric resolution.

The present approach should also be viewed in relation to higher-order and improved shear deformation theories. Such formulations may eliminate the need for an explicit shear correction factor by enriching the through-thickness kinematics or by introducing more

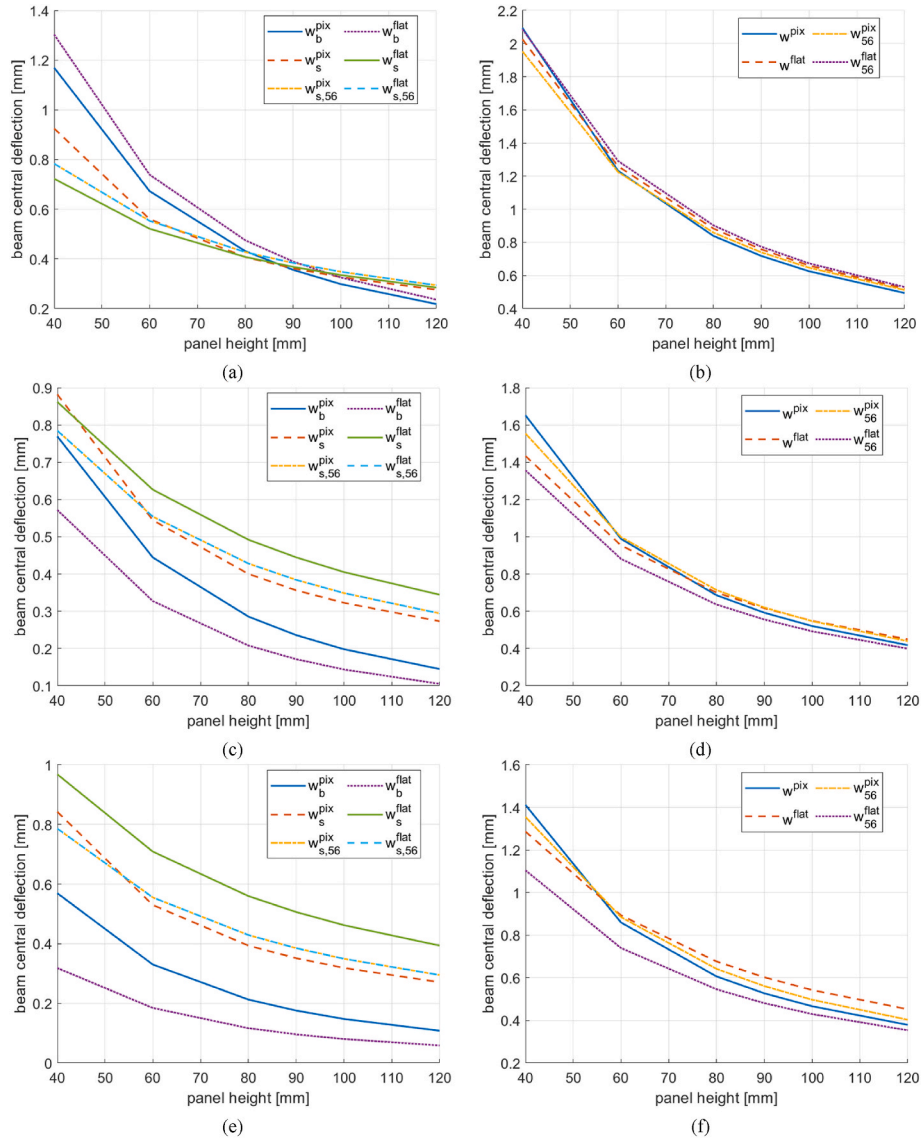


Fig. 5. Plate-strip deflection comparison for three facing thicknesses t_f : (a, c, e) decomposition into bending and shear components; (b, d, f) total mid-span deflections predicted by the pixel-based model, the EI-equivalent flat model, and the engineering benchmark with $k_s = 5/6$, shown as functions of panel height for three facing thicknesses: (a, b) $t_f = 1.0$ mm, (c, d) $t_f = 1.5$ mm, and (e, f) $t_f = 2.0$ mm.

advanced stress assumptions. Their advantage is a potentially more accurate representation of local through-thickness fields, especially in thick, curved, functionally graded, or dynamically loaded structures. Their disadvantage, from a routine engineering perspective, is the increased formulation and implementation complexity. The present method deliberately keeps the FSDT kinematic structure and improves only the transverse shear stiffness through an energy-consistent correction factor. This makes it less general than higher-order theories, but easier to integrate into standard plate and shell workflows. A full 3D solid finite element validation is outside the scope of the present study. The intent is to provide an energy-consistent identification of k_s compatible with FSDT-type models and to quantify relative trends across corrugated geometries. Within this scope, the pixel-based integration serves as a geometry-resolved reference that preserves the equilibrium-driven shear-form function and captures stiffness localization effects without solving a 3D boundary-value problem.

The plate-strip deflection results provide an additional, response-level comparison between the two representations. Tables 4–6 show that transverse shear contributes substantially to the mid-span deflection for the investigated family of geometries and load case, with the

shear component w_s often comparable to, or exceeding, the bending component w_b for larger h (Tables 4–6; Fig. 5a–c,e). This observation is consistent with the low shear stiffness of the core and highlights why geometry-consistent shear correction becomes critical even when bending stiffness is accurately captured. Comparing the total deflections w_{pix} and w_{flat} further shows that residual differences are dominated either by small numerical tolerances in the EI-matching step or by differences in how shear is represented in the simplified cross-section, rather than by the bending term alone (Tables 7–9; Fig. 5b–d,f).

The engineering benchmark using $k_s = 5/6$ with core-only shear serves as a transparent reference to quantify how far a classical constant correction departs from the energy-consistent identification. Because the benchmark is constructed to preserve the product $G_c A_c$ (and $G_c^* A_c^*$ in the flat replacement), the benchmark shear term is internally consistent between pixel and flat descriptions, and the remaining deviation from the energy-consistent predictions reflects the limitations of adopting a constant correction factor and a simplified shear-carrying mechanism. The comparison in Tables 4–9 and Fig. 5 shows that the core-only 5/6 assumption can be close for selected configurations, but noticeable deviations occur for other heights and facing thicknesses, indicating that it

is not universally reliable for corrugated sandwich cross-sections with strong stiffness heterogeneity. In this sense, the present framework is useful not only for identifying geometry-consistent k_s , but also for mapping when classical assumptions remain acceptable and when they become inaccurate.

The proposed methodology should be interpreted within the context of its underlying modeling assumptions. First, the identification of the shear correction factor is performed within the framework of first-order shear deformation theory (FSDT). Consequently, the obtained k_s values are energetically consistent with the adopted reference shear stiffness G_{ref} and the assumed shear-form function, but they do not constitute a full three-dimensional elasticity solution. The objective of the present work is not to replace 3D solid modeling, but to provide a physically transparent and computationally efficient calibration of transverse shear stiffness for reduced-order plate and shell formulations.

Second, in the layered closed-form formulation, the geometric shear-form function is assumed to follow the classical parabolic distribution associated with rectangular sections. While this choice is consistent with standard FSDT practice, it does not explicitly account for material-dependent warping effects. For corrugated configurations in which the soft core fully occupies the profiled regions formed by the facings, this limitation is mitigated by the pixel-based energy integration, which captures stiffness heterogeneity and shear-energy localization at the cross-section level. Nevertheless, the kinematic assumptions remain those of FSDT, and higher-order shear deformation effects are not explicitly modeled.

Third, the pixel-based formulation relies on cross-sectional discretization and energy quadrature, without solving a 3D boundary-value problem. Although this approach enables efficient evaluation of geometry-induced stiffness redistribution, it does not resolve local stress concentrations, contact phenomena within corrugation folds, or potential local plate-bending effects in the metallic facings. The method therefore targets global stiffness characterization rather than detailed stress analysis.

Finally, the benchmark study presented in Section 3 is intentionally restricted to a beam-type strip idealization in order to isolate bending and transverse shear contributions under a consistent reference stiffness convention. The conclusions regarding relative trends of k_s and global compliance should therefore be interpreted within this reduced-order setting. Extension to full plate behavior and comparison with 3D finite element solutions constitute a natural direction for future investigation.

Experimental validation was not included in the present study because the objective was to formulate and verify an energy-consistent identification procedure for reduced-order FSDT models. Nevertheless, experimental testing of representative corrugated sandwich panels, combined with detailed three-dimensional finite element simulations, would be necessary to assess the predictive accuracy of the proposed correction factors for a specific manufactured system. This aspect is therefore identified as an important direction for future work.

Table 10 summarizes the applicability, advantages, and limitations of the modelling approaches discussed in this study.

5. Conclusions

This work presented a pixel-based, energy-consistent identification of the transverse shear correction factor for corrugated sandwich cross-sections with shear-deformable cores and assessed an EI-equivalent three-layer flat replacement. The proposed framework combines a closed-form layered formulation with a pixel-based formulation capable of representing spatially complex core-facing layouts. The results show that both the effective bending stiffness $(EI)_{pix}$ and the identified shear correction factor k_s^{pix} vary systematically with the cross-section height h and facing thickness t_f , confirming that shear correction in such stiffness-heterogeneous configurations is strongly geometry-dependent.

A key finding is that the identified k_s values may be much smaller

Table 10
Applicability, advantages, and limitations of the considered modelling approaches.

Modelling approach	Applicability	Advantage	Limitation
Layered closed-form formulation	Suitable for flat sandwich plates or corrugated facings that can be represented by equivalent homogeneous layers	Provides an analytical and computationally inexpensive estimate of the shear correction factor	Becomes less reliable when fully core-filled corrugated profiles cannot be represented by distinct equivalent layers
Pixel-based formulation	Suitable for corrugated cross-sections with fully core-filled profiled regions and spatially complex material layouts	Accounts for geometry-induced shear-energy localization without solving a 3D boundary-value problem	Provides a global stiffness correction, but not detailed local 3D stress fields
EI-equivalent flat surrogate	Suitable for reduced-order parametric analyses in which the global bending stiffness must be preserved	Enables the use of a simple flat geometry in standard plate and shell models	Represents local corrugation effects only indirectly through equivalent parameters
Core-only shear assumption with $k_s = 5/6$	Suitable only for preliminary estimates of classical sandwich panels with clearly dominant core shear deformation	Offers a very simple engineering approximation	May be inaccurate for corrugated, stiffness-heterogeneous, or facing-participating cross-sections
Higher-order or improved shear deformation theories	Suitable for problems requiring refined through-thickness kinematics, local stress recovery, vibration analysis, or thickness-stretching effects	Can reduce or eliminate the need for an explicit shear correction factor	Requires more complex formulation and implementation
Full 3D finite element modelling	Suitable for validation studies, local stress analysis, interface effects, contact, damage, or local buckling	Provides the most detailed mechanical representation	Computationally expensive and less convenient for broad parametric studies

than the classical value 5/6. This does not indicate a numerical inconsistency, but follows from the adopted reference stiffness and from the physical mechanism of shear-energy localization in the compliant core. In corrugated sandwich cross-sections with stiff metallic facings and a soft core, the reference stiffness may be strongly influenced by the facings, whereas the effective shear compliance remains governed mainly by the core. The shear correction factor therefore acts as an energy-consistent scaling coefficient for the transverse shear stiffness rather than as a universal material or geometric constant.

The EI-equivalent flat replacement reproduced the trends of the pixel-based shear correction factor with good accuracy within the present energy-equivalence identification. This suggests that, after bending calibration and consistent shear-stiffness normalization, a simplified flat surrogate may be useful for reduced-order parametric studies. However, the flat surrogate cannot fully represent local corrugation effects or the detailed distribution of the soft core within the profiled regions formed by the corrugated facings. The pixel-based formulation is therefore

preferable when the actual geometry of the corrugated cross-section must be retained at the stiffness-identification level.

The main advantage of the proposed method is its compatibility with standard Mindlin–Reissner plate and shell models. It improves the transverse shear stiffness used in FSDT without introducing additional degrees of freedom or requiring a full three-dimensional boundary-value solution. The method is therefore suitable for engineering-oriented modelling, parametric analyses, and preliminary optimization of corrugated sandwich panels with soft cores.

The limitations of the approach should also be emphasized. The formulation provides a cross-section-based global stiffness correction and does not resolve local three-dimensional stress concentrations, interface damage, contact effects, local plate bending in corrugated facings, or thickness-stretching deformation. The numerical value of k_s also depends on the adopted reference shear modulus and must be interpreted together with that convention. Finally, the present study does not include experimental validation. Future work should therefore include comparison with detailed 3D finite element simulations and experimental tests on representative corrugated sandwich panels.

CRediT authorship contribution statement

Tomasz Garbowski: Conceptualization, Formal analysis, Methodology, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Anna Szymczak-Graczyk:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Validation, Writing – original draft. **Zbigniew Pozorski:** Formal analysis, Funding acquisition, Investigation, Resources, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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