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Approximate 3-D model for analysis of laminated plates with arbitrary lay-ups, loading and boundary conditions

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Abstract—Available exact solution techniques of elasto-static problems entail limitations on the choice of lay-ups, loading and boundary conditions and impose restrictions on strain and stress fields as well, to overcome algebraic difficulties inherent to modeling of laminated and sandwich composites. Therefore in fact they become unsuitable for testing accuracy of modern laminated plate theories aiming to very accurately describing 3-D stress fields in real conditions of use of multilayered composites, nowadays widespread in engineering applications. To overcome the assumption of too restrictive hypotheses, an approximate 3-D solution technique is proposed and assessed that is able to automatically solve problems which due to the lay-ups, loading and boundary conditions assumed would not be solved with the exact techniques available. A quite general, accurate structural model is developed that comes to constitute a generalization of available physically-based zig-zag theories, being free from through-thickness assumptions and because zig-zag functions are not explicitly contained, the layerwise contributions being represented by the redefinition of coefficients of the through-thickness series expansion. It is based solely on the prescriptions of the theory of elasticity, i.e., displacement and stress compatibility at interfaces, fulfillment of local equilibrium equations at points across the thickness and of stress boundary constraints. A truncated expansion series of trial functions and unknown amplitudes is used to represent variables, whose coefficients are determined in exact form using a symbolic calculus tool that enforces all elasticity constraints and in conjunction with Rayleigh-Ritz and Lagrange multipliers methods.

Keywords—Composite and sandwich plates, zig-zag theories, interlaminar transverse shear/normal stress continuity, localized and distributed loadings, FEA 3-D, elastostatic solutions.

I. INTRODUCTION

Laminated and sandwich composites are progressively replacing traditional metallic materials in various engineering applications, thanks to their superior properties in terms of specific strength and stiffness, energy absorption, fatigue and corrosion properties.

Due to strongly different in-plane and transversal elastic properties that distinguish these materials, 3-D stress fields take place that condition formation and growth of local damage and failure mechanisms and that require specific structural models. The main aspect to highlight is that their displacement field must be C^0 -continuous (zig-zag effect), so that appropriate slope discontinuities occurs and consequently local equilibrium equations can be satisfied at layer interfaces. A multitude of theories is to date available that differently account for the mentioned layerwise effects and which so have a different order of accuracy and different computational costs. A broad discussion of this matter is given by Carrera and co-workers [1-4], Vasilive and Lur'e [5], Reddy and Robbins [6], Lur'e, and Shumova [7], Noor et al. [8], Altenbach [9], Khandan et al. [10] and Kapuria and Nath [11] and in the book by Reddy [12].

Due to the inevitable limiting hypotheses a priori formulated, laminated plate theories may no longer be accurate for arbitrary lay-ups, loading and boundary conditions and strong transverse anisotropy that are typical of some practical applications. As most of the assessments have been carried out just considering cross-ply lay-ups, sinusoidal heap loading and simply-supported edges, since exact solutions can be determined and used for comparisons, and unfortunately usually a mild variation of thickness and elastic properties of layers, what the limits of available theories may be is not well known in general.

Exact solutions, of which by way of example the papers by Brischetto [13] (static analysis of multi-layered plates and shells), Yang et al. [14] (free vibration analysis of laminated, box and sandwich Icardi [15] (exact solution for a damaged sandwich beam with laminated faces) and by Ren [16] (laminated shell in cylindrical bending) are cited, usually assume thin constituent layers in order plane strain conditions can be postulated. In addition, they assume symmetric lay-ups, simply-supported conditions and sinusoidal loading, because solutions can be assumed in trigonometric form. Then, stresses are

assumed across the thickness and strain compatibility is enforced, in accordance with Pagano [17,18] who pioneered the technique for finding exact solutions.

The algebraic complexity forced researchers to take on the previous assumptions, but they cannot be appropriate for exhaustively testing theories and their finite elements, as is evident. Clamped edges, layers with very different material properties and thickness and localised distributed loading should instead be considered since they are more probative, as highlighted by the results of theories in disagreement with each other [19-21] for the cited cases, while under conditions that enable the existence of exact solutions they agree. So approximate, but yet accurate, 3-D, closed form solutions (theoretical foundations comprehensively discussed by Reddy and Chao [22] and Yakimov [23]) suitable for arbitrary assumptions have to be considered to test theories and finite elements. Consequently approximate closed form approaches must be applied whose variables are expressed as a truncated series expansion of assumed trial functions, the related unknown amplitudes being determined using e.g. Rayleigh-Ritz method, provided that restrictive assumption that can nullify the desired generality are not introduced.

It must be considered that 3-D FEA cannot be reliable under arbitrary assumptions of loading and boundary conditions and therefore cannot be considered as the only comparison result for theories, because elements in displacement-based form do not exactly satisfy local equilibrium equations, while mixed finite elements [24] may be affected by geometric and material singularity edge effects and anyway both may be strongly influenced by local effects of loading and constraints.

A tool that can be used to prevent the need of assuming restrictive hypotheses to overcome the algebraic difficulties inherent to the development of a quite general structural model is symbolic calculus. Although one would expect a widespread use of this tool, at the best of authors' knowledge still no applications of it (except [19-21]) is available in the nowadays literature, despite it is particularly suitable for easily manipulating the intricate algebraic passages that follows when arbitrary loading and boundary conditions are assumed.

Aiming to avoid having to assume too restrictive hypotheses dictated by algebraic difficulties when solving structural problems of laminated and sandwich composites (the latter being assumed in homogenized form as a set of layers with very different properties) with quite general lay-up, elastic moduli, loading and boundary conditions, in the present paper the structural models [19-21] across the thickness and their (for the truth few and not too much restrictive) hypotheses are replaced with a general representation of variables, which is able to capture the salient aspects while minimizing computational costs, so to provide a quick and accurate tool that furnishes a 3-D solution of comparison. The purpose is to develop an approximate but accurate 3-D solution which does not introduce simplifying a priori hypotheses about through-thickness kinematics, strain and stress fields, which respects all physical and elasticity constraints and so which comes to constitute a generalization of zig-zag theories [19-21] that likewise uses a fixed number of d.o.f. irrespective of the number of layers. No zig-zag layerwise functions are incorporated, the coefficients of the displacement field playing the role of layerwise functions themselves being redefined across the thickness through the enforcement of physical constraints. The latter are constituted by interfacial stress and displacements compatibility, by stress boundary conditions, by local equilibrium equations at points across the thickness, as well as physical constraints specifying the nature of solutions within the domain. The characteristic feature is that all constraints are satisfied in exact form through use of a symbolic calculus tool that provides once and for all expressions deriving from the enforcement of constraints.

The analytical solution is searched as a truncated expansion series of trial functions and unknown amplitudes (like, e.g. Vel and Batra [25]) using Rayleigh-Ritz method, the kinematic variables constituting the unknowns being expanded in the in- and out-of-plane directions, a structural model that is configured in advance being lacking. As a consequence, the proposed approach assumes characteristics similar to the search for closed form solutions using laminated plate theories [22,23]. But, at the same time, it is similar to the search of exact solutions [13-18], given the lack of a structural model assumed a priori and the imposition of wanted characteristics to solutions. So, ultimately, the solution is configured through the choice of the constraints imposed, consequently it can be changed at will by the user in the applications. The crucial difference is that enforcements are solved via symbolic calculus, thus allowing for more general situations. In particular, the load can be arbitrarily chosen, it being expressed as an analytical function of the coordinates that is managed exactly. Anyway, the solution is get automatically and quickly by the symbolic calculus tool, irrespective of the choices made. A number of challenging benchmarks with strong layerwise effects are considered in the applications (see Tables 1 and 2) to demonstrate accuracy and efficiency of the proposed approach. Results by 3-D FEA [24], by multilayered theories with different characteristics retaken from [20,21] and exact solutions, where available, are used for comparisons.

TABLE 1
GEOMETRY, LOADING AND BOUNDARY CONDITIONS.

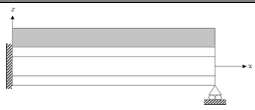
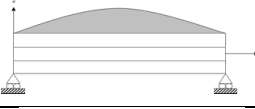
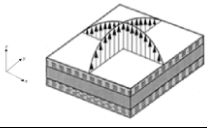
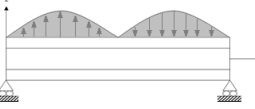
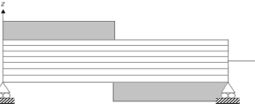
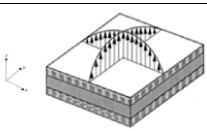
Case	Layer thickness	Material		Loading	Lx/h	Ly/Lx
a	$[(2h/7) / (4h/7) / (h/7)]$	[n/n/n]		$p^0(x) = p_u^0$ if $0 \leq x \leq L_x$	14.286	-
b	$[(h/3)_3]$	[p ₃]		$p^0(x) = p_u^0 \sin(\pi x / L_x)$ if $0 \leq x \leq L_x$	4	-
c	$[(h/3)_3]$	[c1/c1/c1]		$p^0(x, y) = p_u^0 \sin(\pi x / L_x) \sin(\pi y / L_y)$ if $0 \leq x \leq L_x$ and $0 \leq y \leq L_y$	4	3
d	$[0.1h / 0.4h]_s$	[Gr-Ep/Foam] _s		$p^0(x) = p_u^0 \sin(2\pi x / L_x)$ if $0 \leq x \leq L_x$	10	-
e	$[0.1h_2/0.2h_3/0.1h_2]$	[pf ₂ /pvc/hh/ pvc/pf ₂]		$p^0(x) = \begin{cases} p_u^0 & \text{if } 0 \leq x \leq L_x / 2 \\ -p_u^0 & \text{if } L_x / 2 \leq x \leq L_x \end{cases}$	8	-
f	$[0.2h/0.7h/0.1h]$	[c2/c2/c2]		$p^0(x, y) = p_u^0 \sin(\pi x / L_x) \sin(\pi y / L_y)$ if $0 \leq x \leq L_x$ and $0 \leq y \leq L_y$	4	3

TABLE 2
MECHANICAL PROPERTIES

Material name	c1 [iso]	c2 [iso]	Foam	Gr-Ep	hh	n [iso]	p	pf	pvc
E1[GPa]	-	-	0.035	132.38	0.250	-	172.4	25000	250
E2[GPa]	-	-	0.035	10.76	0.250	-	6.89	1000	250
E3 [GPa]	M1	M2	0.035	1.076	2.5	M3	6.89	1000	250
G12 [GPa]	-	-	0.0123	5.65	0.001	-	3.45	500	96.2
G13 [GPa]	-	-	0.0123	5.65	0.875	-	3.45	500	96.2
G23 [GPa]	-	-	0.0123	3.61	1.750	-	1.378	200	96.2
v12	0.34	0.34	0.4	0.24	0.9	0.33	0.25	0.25	0.3
v13	0.34	0.34	0.4	0.24	3×10^{-5}	0.33	0.25	0.25	0.3
v23	0.34	0.34	0.4	0.49	3×10^{-5}	0.33	0.25	0.25	0.3
M1 $E_v/E_u=5/4, E_v/E_c=10^5$; M2 $E_v/E_u=5/4, E_v/E_c=10^4$; M3 $E_v/E_l=1.6, E_v/E_c=166.6 \cdot 10^5$; [iso]=isotropic $E_1=E_2=E_3 \quad G_1=G_2=G_3$									

II. THEORETICAL FRAMEWORK

Hereafter requirements of the present approximate 3-D solution approach and its peculiar features across the thickness, notations, the solution technique itself, in-plane representations used in each single case and the relative order of expansion are discussed in sequence.

2.1 Requirements

Layers are assumed to have linear elastic anisotropic properties, which may be distinctly different from one another, in addition, they may have a different thickness, to enable considering a strong transverse anisotropy.

In accordance with the intended aim of this paper, the following further requirements must be respected.

With regard to stress fields, no restrictive a priori assumptions are made, except out-of plane components and also the through-thickness gradient of the transverse normal stress must be continuous at interfaces, as prescribed by the elasticity theory. Self-equilibrated stress fields are not assumed a priori, since the equilibrium is satisfied in approximate integral form within the governing functional and in point-format few selected points across the thickness. Stress-free boundary conditions on upper and lower bounding faces are identically satisfied within the symbolic calculation process, but any other arbitrary condition of interest could be freely imposed in accordance with the chosen loading.

Displacements could be assumed to be either continuous or discontinuous (so to use cohesive models, e.g. for studying delamination) at interfaces. However, in the present case the choice is limited to the first option. No restriction is made about the order and therefore to the number of coefficients of the expansion representing displacements across the thickness (1), it being determined by the number of constraints that one intends to impose case by case. As will be specified below, in numerical applications a low but sufficiently accurate order of expansion is chosen, which the same for each layer is. As well, any kind of in-plane representation can be used.

Here the Total Potential Energy functional (TPE) is chosen as governing functional, loadings being conservative, which is solved in a discrete form using Rayleigh-Ritz method, although any other functional could be used to find the solution in conjunction with a symbolic calculus tool.

In fact, like for any other assumption of the procedure, it is sufficient expressing the relative formula, then the calculation proceeds automatically.

2.2 Notations

A Cartesian coordinate reference system (x, y, z) is assumed as the reference frame, (x, y) representing the reference plane Ω and consequently z being the thickness coordinate. The position of Ω can be assumed arbitrarily across the thickness, so to avoid the possible zeroing of coefficients at $z=0$ for certain lay-ups and assumed forms of solution.

Tensor notation is used to make formulas compact, so symbols x, y, z can be replaced by Greek letters, i.e. $\alpha = 1, 2 \equiv x, y$; $\zeta = 3 \equiv z$, then Einstein summation convention is used. A comma is used to indicate spatial derivatives, e.g. $(\cdot)_{,x} = \partial/\partial x$, $(\cdot)_{,z} = \partial/\partial z$.

The overall thickness of the laminate is indicated by h , while L_x and L_y symbolize the plate side-length in the x - and y -directions. Layers are assumed to have uniform thickness h^k and to be perfectly bonded to each other (bonding resin interlayer disregarded).

To symbolize that a quantity belongs to a specific layer, e.g. k -th one, subscripts $_k$ or superscripts k are affixed, while u and l indicate that quantities are evaluated at upper or lower faces of the laminated structure, respectively. Accordingly, $z^{(k)+}$ and $z^{(k)-}$ represent the thickness coordinates just after or just before the interface k , respectively.

Strains, which are assumed to be infinitesimal, and stresses are symbolized respectively by ε_{ij} and σ_{ij} , while in-plane and transverse components of elastic displacements are indicated as u_α and u_ζ .

The functional d.o.f. are represented by the coefficients constituting the amplitudes of the series expansion of displacements. Because a fixed representation (namely, shape and order) is used across each constituent layers. Characteristic feature, coefficients are recalculated layer by layer by enforcing constraints (see section 2.3.1). As a consequence, the number of d.o.f. does not depend depends on the number of constituent layer (as will be specified in detail below).

Because the representation is the same for each layer but coefficients are re-calculated, the displacement field will be affected by an index j representing the counter of computational layers, whose number can be equal, greater or lower than the number of physical layers k .

2.3 Structural model

The following displacement field is postulated across the thickness:

$$\begin{aligned}
 u_{\alpha}^j &= \sum_{k=0}^{n_{\alpha}} \sum_{p=1}^P \sum_{m=1}^M \left[{}_{p m}^j a_k^{\alpha}(x, y) z^{(k-1)} \right] \\
 u_{\zeta}^j &= \sum_{k=0}^{n_{\zeta}} \sum_{p=1}^P \sum_{m=1}^M \left[{}_{p m}^j b_k^{\alpha}(x, y) z^{(k-1)} \right]
 \end{aligned} \tag{1}$$

It could be noticed that that it is a completely generic representation and therefore is characterized by the absence of restrictive assumptions across the thickness, at the contrary of laminated plate models.

Instead of introducing a priori assumptions like in the plate models, here the behavior of the structure is described by the imposition of the appropriate physical constraints that come to characterize the behavior of the structure within the domain (here means across the thickness) and at the boundary, as outlined forward. Therefore (1) constitutes the approximate solution of the resulting boundary value problem that will be discussed in detail below.

The representation chosen (1) is the product of truncated series expansions, respectively in (x, y) and z (where z is calculated starting from Ω), whose coefficients are the unknowns, namely the functional degrees of freedom. In-plane expressions of contributions ${}_{p m}^j a_k^{\alpha}(x, y)$ and ${}_{p m}^j b_k^{\alpha}(x, y)$ are chosen to fulfill constraint conditions on the lateral boundary surface of the laminated structure under examination, so, trial functions a priori individually satisfy the prescribed boundary conditions, where M and P are the maxim expansion order through in-plane directions.

Amplitudes ${}_{p m}^j a_k^{\alpha}$ and ${}_{p m}^j b_k^{\alpha}$ are determined once and for all by the symbolic calculus tool used through the contemporary application of Rayleigh-Ritz, Lagrange Multipliers methods, by stress boundary conditions at upper and lower bounding faces, as well as by imposing the satisfaction of interfacial displacements and stress conditions and the fulfillment of local equilibrium equations at points selected across each computational J or physical layer $J=i$.

However, even if the solution search methodology is classic, the use of symbolic calculus makes it worthy of note, owing to its peculiar characteristics. Indeed, symbolic calculus enables the simultaneous imposition of local equilibrium equations, interfacial displacement and stress compatibility conditions across the thickness (which can be chosen and changed at the discretion of the operator, as the calculation proceeds anyway automatically) and an arbitrary choice of loading obtaining in any case quickly and once and for all the exact relationships among involved quantities, without having to resort to restrictive assumptions to overcome the complexity of the calculation, as would happen by hand.

As mentioned above in 2.2, Ω can be chosen at any position across the thickness and then changed as desired by the user, because symbolic calculus tools finds always the same solution irrespective for this choice, provided that the set of physical constraints remains the same. In this way it is prevented that stresses are erroneously predicted to vanish for $z=0$ due to the possible, although unlikely (given the high degree of generality), zeroing of coefficients that could occur in some cases. So, it is not necessary to include any zig-zag functions or define a specific role or position for any coefficients. Results of the present theory (1) with two different reference frames are reported for case a.

The unknown amplitudes, which constitute the d.o.f. of the problem, are fixed in number because they just depend on the expansion order chosen a priori across the thickness of each layer, which is assumed the same for all layers (n_{α} and n_{ζ}) and by in-plane expansion orders M and P . Expressions coming from the enforcement of the constraints are re-determined for each lamina as functions of the unknowns, that is the amplitudes in (1), whose number depends on the order of expansion chosen and remains fixed. As physical constraints are enforced, the present structural model must be included in the context of physically-based theories.

In this paper, a cubic/forth-order through-thickness representation is assumed because numerical tests revealed this degree of expansion to be appropriate for finding accurate solutions in all the cases considered. It has to be pointed out that that a such expansion order is much lower compared to structural models that are more in vogue today and do not impose physical constraints [1-12]. Therefore a significant advantage is constituted by the fact that imposing all the relevant physical constraints, a low order of expansion is sufficient.

Note that the order of expansion could be exchanged between in-plane and out of plane components (1) without the results changing. Indeed, symbolic calculus finds always the same exact relations among quantities when the same set of constraints

is imposed. It should also be noted that users can freely choose the sequence of what condition (which will be explicitly defined below) to impose first, as well as the functional to be used and the representation since calculations proceed automatically, as already mentioned above.

It is reminded that the final result obtained in this way accounts for the imposition of constraints across the thickness, i.e. the continuity of displacements and stresses (which can be relaxed if desired), stress boundary conditions and local equilibrium equations.

2.3.1 Structural model construction and solution procedure

The construction of the computational model starts by imposing the various constraint conditions starting always from the lower lamina, then it progressively precede up to the upper one and finally the amplitudes are determined by the Rayleigh-Ritz method.

For each layer, as results from (1), there are 13 coefficients to be defined by enforcing physical constraints across the thickness for a cubic/quartic expansion. Therefore an overall number of $13 \times N \times P \times M$ computations is required if in total the layers are N and P and M are the maximal expansion orders along x and y axis respectively.

Before proceeding it is necessary to distinguish the upper and lower layers from ones inside, since the calculation of the coefficients is carried out differently. Note that although the coefficients ${}_{p m}^j a_k^\alpha$ and ${}_{p m}^j b_k^\alpha$ of (1) do not have a specific a priori fixed role, so they can be determined by exchanging freely the conditions to be enforced for computing each of them, because always the same final result will be obtained, hereafter a specific choice is made in order to explain the procedure.

At interfaces of intermediate layers, the following four stress compatibility conditions [15] are enforced

$$\sigma_{\alpha\zeta}({}^{(k)}z^+) = \sigma_{\alpha\zeta}({}^{(k)}z^-); \quad \sigma_{\zeta\zeta}({}^{(k)}z^+) = \sigma_{\zeta\zeta}({}^{(k)}z^-); \quad \sigma_{\zeta\zeta,\zeta}({}^{(k)}z^+) = \sigma_{\zeta\zeta,\zeta}({}^{(k)}z^-) \quad (2)$$

which follows in a straightforward way from local equilibrium equations

$$\sigma_{\alpha\beta,\beta} + \sigma_{\alpha\zeta,\zeta} = b_\alpha \quad ; \quad \sigma_{\alpha\zeta,\alpha} + \sigma_{\zeta\zeta,\zeta} = b_\zeta \quad (3)$$

because the derivability of stresses must be guaranteed. The following three displacement continuity conditions must also be enforced at interfaces

$$u_\alpha({}^{(k)}z^+) = u_\alpha({}^{(k)}z^-); \quad u_\zeta({}^{(k)}z^+) = u_\zeta({}^{(k)}z^-) \quad (4)$$

otherwise as an alternative a suitable cohesive model could be used. Because a total number of $7 \times (N-1)$ physical constraints is enforced at each interface through (2) and (4), then $6 \times (N-1) + 13$ are still undetermined, out of a total of $13 \times N$.

However, $6 \times N$ relations could be computed by imposing the fulfillment of (3) at two points arbitrarily chosen across the thickness of the N constituent layers, but in this way the eight boundary conditions (5) could not be satisfied.

Since the first interface has not yet been met when the lower bounding layer is considered, it is impossible to enforce the 7 continuity conditions of stress and displacements discussed above for the first layer, but instead the following 4 boundary conditions

$$\sigma_{\alpha\zeta} = \sigma_{\zeta\zeta,\zeta} = 0 \quad ; \quad \sigma_{\zeta\zeta} = p^0(\pm) \quad (5)$$

could be imposed ($p^0(\pm)$ is the continuous or discontinuous mathematical function representing the loading acting over the upper⁺ or lower⁻ layers) and the same applies to the upper lamina, because there are no further interfaces to consider. In the present paper, two sets of equilibrium conditions are enforced in the inner layers, while just one is enforced in the outer layers. Once this is done, the remaining free variables, which constitute the d.o.f. (it is reminded that the total number of unknowns is $13 \times N \times P \times M$, of which P and M depend on in-plane expansion order) are determined using Rayleigh-Ritz method. If a greater number of equilibrium points is needed, it is sufficient to subdivide the physical layer into computational ones.

Because in isotropic beams and plates, which anyway are not the cases for which the present technique is developed, no stress compatibility relations can be enforced being already identically satisfied, a greater number of amplitudes must be determined by the Rayleigh-Ritz method.

2.3.2 Trial Functions

Once constraints are imposed as outlined above, the process continues by assuming appropriate in-plane expressions of coefficients and applying the Rayleigh-Ritz method. The whole solution procedure is summarized in Figure 1.

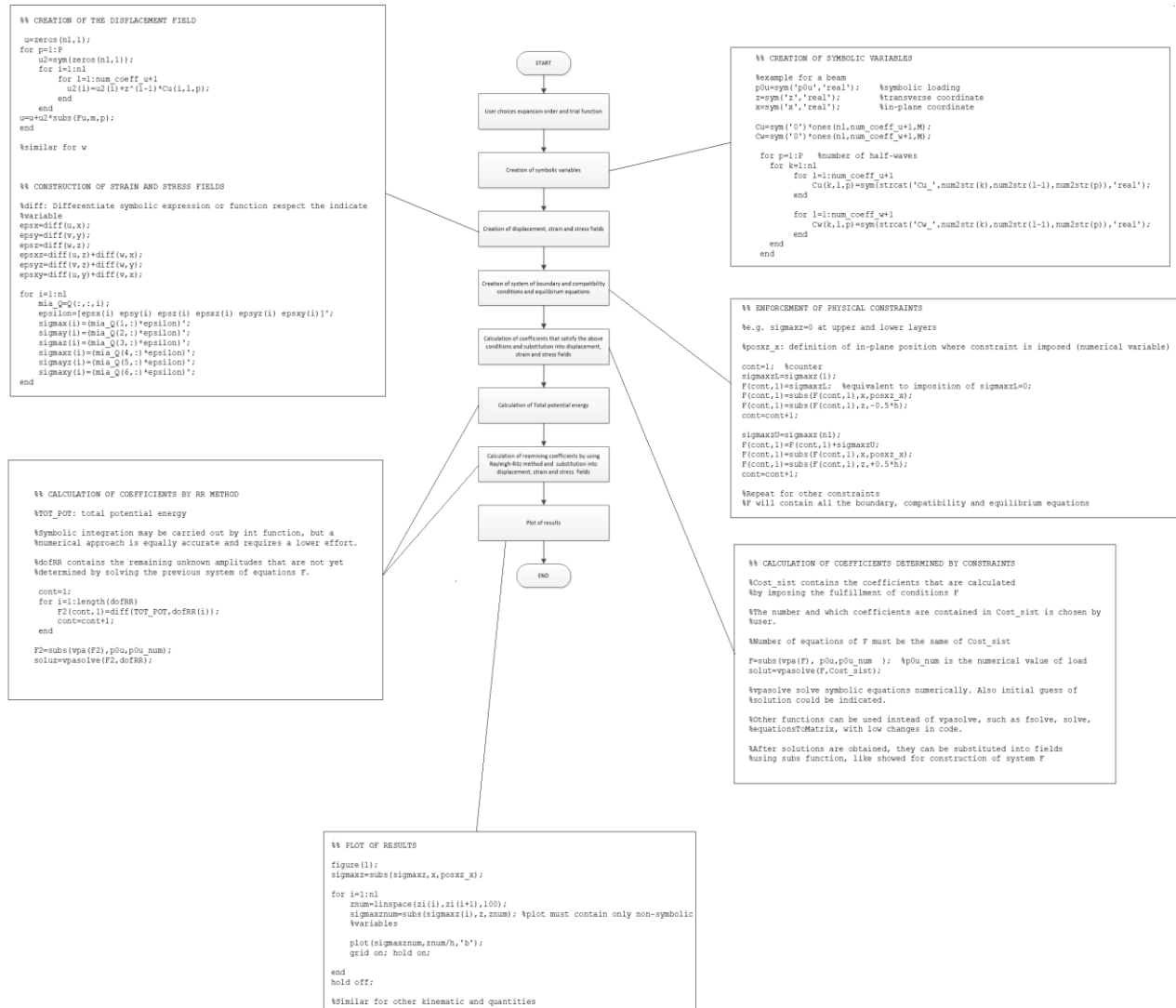


FIGURE 1: Schematic representation of the solution procedure.

If Δ symbolizes in turn ${}_p m^j a_k^\alpha(x, y)$ and ${}_p m^j b_k^\alpha(x, y)$ the in-plane contribution to solution (1) is postulated as:

$$\Delta = \sum_{i=1}^{m_\Delta} A_\Delta^i \mathcal{R}^i(x, y) \tag{6}$$

where A_Δ^i are unknown amplitudes and $\mathcal{R}^i(x, y)$ are trial functions specific to each case, which individually satisfy the prescribed, (also called geometric) boundary conditions, while mechanical also (called natural) boundary conditions are satisfied using Lagrange multipliers method. Table 3 reports the expressions of $\mathcal{R}^i(x, y)$ for each specific case, along with the expansion order and normalizations used. Trial functions are chosen in order to fulfil the following sets of boundary conditions specific for each of the examined cases.

TABLE 3
TRIAL FUNCTIONS, EXPANSION ORDER AND NORMALIZATION.

Case	Trial functions (6)	Expansion	Normalization
a	$\mathfrak{R}^m_\alpha(x, y) = \left(\frac{x}{L_x}\right)^m$; $\mathfrak{R}^m_\zeta(x, y) = \left(\frac{x}{L_x}\right)^m$	9	$\bar{u}_\alpha = \frac{u_\alpha(L_x, z)}{hp^0}$ $\bar{u}_\zeta = \frac{u_\zeta(L_x, z)}{hp^0}$ $\bar{\sigma}_{\alpha\alpha} = \frac{\sigma_{\alpha\alpha}(L_x, z)}{p^0(L_x/h)^2}$ $\bar{\sigma}_{\alpha\zeta} = \frac{A\sigma_{\alpha\zeta}(L_x, z)}{p^0 L_x}$ $\bar{\sigma}_{\zeta\zeta} = \frac{\sigma_{\zeta\zeta}(L_x, z)}{p^0}$
b	$\mathfrak{R}^m_\alpha(x, y) = \cos\left(\frac{m\pi x}{L_x}\right)$; $\mathfrak{R}^m_\zeta(x, y) = \sin\left(\frac{m\pi x}{L_x}\right)$	1	$\bar{u}_\alpha = \frac{E_2 u_\alpha(0, z)}{hp^0}$ $\bar{u}_\zeta = \frac{100h^3 E_2 u_\zeta\left(\frac{L_x}{2}, z\right)}{L_x^4 p^0}$ $\bar{\sigma}_{\alpha\alpha} = \frac{\sigma_{\alpha\alpha}\left(\frac{L_x}{2}, z\right)}{p^0}$ $\bar{\sigma}_{\alpha\zeta} = \frac{\sigma_{\alpha\zeta}(0, z)}{p^0}$ $\bar{\sigma}_{\zeta\zeta} = \frac{\sigma_{\zeta\zeta}\left(\frac{L_x}{2}, z\right)}{p^0}$
c	$\mathfrak{R}^{m,n}_\alpha(x, y) = \cos\left(\frac{m\pi}{L_x}x\right) \sin\left(\frac{n\pi}{L_y}y\right)$; $\mathfrak{R}^{m,n}_\beta(x, y) = \sin\left(\frac{m\pi}{L_x}x\right) \cos\left(\frac{n\pi}{L_y}y\right)$; $\mathfrak{R}^{m,n}_\zeta(x, y) = \sin\left(\frac{m\pi}{L_x}x\right) \sin\left(\frac{n\pi}{L_y}y\right)$	1	$\bar{u}_\alpha = \frac{E_{1,core} u_\alpha\left(0, \frac{L_y}{2}, z\right)}{p^0(L_x^3/h^2)}$ $\bar{u}_\beta = \frac{u_\beta\left(\frac{L_x}{2}, 0, z\right)}{hp^0}$ $\bar{u}_\zeta = \frac{u_\zeta\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{hp^0}$ $\bar{\sigma}_{\alpha\alpha} = \frac{\sigma_{\alpha\alpha}\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{p^0(L_x/h)^2}$ $\bar{\sigma}_{\beta\beta} = \frac{\sigma_{\beta\beta}\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{p^0(L_x/h)^2}$ $\bar{\sigma}_{\alpha\beta} = \frac{\sigma_{\alpha\beta}(0, 0, z)}{p^0(L_x/h)^2}$ $\bar{\sigma}_{\alpha\zeta} = \frac{\sigma_{\alpha\zeta}\left(0, \frac{L_y}{2}, z\right)}{p^0(L_x/h)}$ $\bar{\sigma}_{\beta\zeta} = \frac{\sigma_{\beta\zeta}\left(\frac{L_x}{2}, 0, z\right)}{p^0}$ $\bar{\sigma}_{\zeta\zeta} = \frac{\sigma_{\zeta\zeta}\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{p^0}$
d	$\mathfrak{R}^m_\alpha(x, y) = \cos\left(\frac{2m\pi x}{L_x}\right)$	1	$\bar{u}_\alpha = \frac{u_\alpha(0, z)}{hp^0}$ $\bar{u}_\zeta = \frac{u_\zeta\left(\frac{L_x}{4}, z\right)}{hp^0}$ $\bar{\sigma}_{\alpha\alpha} = \frac{\sigma_{\alpha\alpha}\left(\frac{L_x}{4}, z\right)}{p^0(L_x/h)^2}$
e	$\mathfrak{R}^m_\zeta(x, y) = \sin\left(\frac{2m\pi x}{L_x}\right)$	1	$\bar{\sigma}_{\alpha\zeta} = \frac{\sigma_{\alpha\zeta}(0, z)}{p^0}$ $\bar{\sigma}_{\zeta\zeta} = \frac{\sigma_{\zeta\zeta}\left(\frac{L_x}{4}, z\right)}{p^0}$
f	$\mathfrak{R}^{m,n}_\alpha(x, y) = \cos\left(\frac{m\pi}{L_x}x\right) \sin\left(\frac{n\pi}{L_y}y\right)$; $\mathfrak{R}^{m,n}_\beta(x, y) = \sin\left(\frac{m\pi}{L_x}x\right) \cos\left(\frac{n\pi}{L_y}y\right)$; $\mathfrak{R}^{m,n}_\zeta(x, y) = \sin\left(\frac{m\pi}{L_x}x\right) \sin\left(\frac{n\pi}{L_y}y\right)$	1	$\bar{u}_\alpha = \frac{u_\alpha\left(0, \frac{L_y}{2}, z\right)}{hp^0}$ $\bar{u}_\beta = \frac{u_\beta\left(\frac{L_x}{2}, 0, z\right)}{hp^0}$ $\bar{u}_\zeta = \frac{u_\zeta\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{hp^0}$ $\bar{\sigma}_{\alpha\alpha} = \frac{\sigma_{\alpha\alpha}\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{p^0(L_x/h)^2}$ $\bar{\sigma}_{\beta\beta} = \frac{\sigma_{\beta\beta}\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{p^0(L_x/h)^2}$ $\bar{\sigma}_{\alpha\beta} = \frac{\sigma_{\alpha\beta}(0, 0, z)}{p^0(L_x/h)^2}$ $\bar{\sigma}_{\alpha\zeta} = \frac{\sigma_{\alpha\zeta}\left(0, \frac{L_y}{2}, z\right)}{p^0}$ $\bar{\sigma}_{\beta\zeta} = \frac{\sigma_{\beta\zeta}\left(\frac{L_x}{2}, 0, z\right)}{p^0}$ $\bar{\sigma}_{\zeta\zeta} = \frac{\sigma_{\zeta\zeta}\left(\frac{L_x}{2}, \frac{L_y}{2}, z\right)}{p^0}$

At simply-supported edges, the following boundary conditions are enforced at $x=0$, $x=L_x$ and $y=0$, $y=L_y$, on the middle plane, whether it represents or not the reference plane Ω :

$$w^0(0, y) = 0 ; w^0(L_x, y) = 0 ; w^0(0, y)_{,xx} = 0 ; w^0(L_x, y)_{,xx} = 0$$

$$w^0(x, 0) = 0 ; w^0(x, L_y) = 0 ; w^0(x, 0)_{,yy} = 0 ; w^0(x, L_y)_{,yy} = 0 \tag{7}$$

L_x, L_y being the length of sides parallel to x, y axes, respectively. In the applications, plates in cylindrical bending are considered, whose boundary conditions are derived in a straightforward way from (7). Obviously, e.g. if (x, z) is assumed as the plane where bending takes place, the appropriate conditions are obtained assuming that variations in the y direction are nil.

At clamped edges, the following constraints are imposed at the middle-plane z^* , which as an example are reported in the case the extreme is at $x=0$:

$$u_{\alpha}(0, z^*) = w_{\zeta}(0, z^*) = w_{\alpha}(0, z^*)_{,x} = 0 \quad (8)$$

In order to simulate that the previous conditions hold identically across the thickness, the following further boundary conditions are enforced:

$$u_{\alpha}(0, z)_{,z} = 0 ; u_{\zeta}(0, z)_{,z} = 0 ; u_{\zeta}(0, z)_{,xz} = 0 \quad (9)$$

In addition, the mechanical boundary condition:

$$\int_{-h/2}^{h/2} \sigma_{xz}(0, z) dz = T \quad (10)$$

is imposed in order to ensure that the transverse shear stress resultant force per unit of width equals the counterpart constraint force T .

The additional support condition $w^0(L, z_l) = 0$ holds at $x=L$ on the lower face z_l at the supported extreme of the propped cantilever beam considered in the numerical applications. In this case, condition (10) is reformulated as:

$\int_{-h/2}^{h/2} \sigma_{xz}(L, z) dz = T_L$. Note that the mechanical boundary conditions defined above are enforced using Lagrange multipliers method.

After expressing $\mathfrak{R}^i(x, y)$ as defined above for the single case, the candidate solution (6) of (1) is substituted into the expression of TPE, which is constructed using the relations, provided by the symbolic that comes from the enforcement of (2) to (5). Loading distributions considered in the numerical applications are represented by the symbolic calculus tool used to construct the present structural model as analytical continuous or discontinuous functions, whose energy contribution is computed exactly.

III. NUMERICAL ASSESSMENTS AND DISCUSSION

Elasto-static benchmarks whose lay-ups, loading and boundary conditions enhance layerwise effects are considered for assessing accuracy and efficiency of the present 3-D approximate solution methodology. They are identified here as cases a to f and can be distinguished in two groups based on their specific characteristics.

The first group consists of cases b and c, for which the exact solution is available and then is retaken as reference solution together with one by 3-D FEA [24]. In other cases, only 3-D FEA is the reference solution. Moreover, results by laminated plate theories are reported, including those of accurate 3-D zig-zag theories such as ZZA and ZZA* [19-21].

Note that 3-D FEA [24] results are obtained using mixed solid finite elements [24] having the three elastic displacements and the three out-of-plane stress components as degrees of freedom are used, which respect the continuity of the above mentioned stresses at layer interfaces, how it is required to be, with no need for post processing, whose accuracy has been amply demonstrated by case applications even with singularities in the field.

These cases are considered for the purpose of assessing the accuracy of the approximate solution 3-D methodology proposed in this paper, thus avoiding that errors related to the approximations introduced can render the interpretation doubtful, as would happen with any approximate solution method whenever it is used as a comparison solution. As a consequence, comparisons between 3-D FEA and exact solution enable to further test accuracy of 3-D FEA [24], in order to avoid that the conclusions drawn for cases a and d to f are not invalidated by doubts concerning calculation errors.

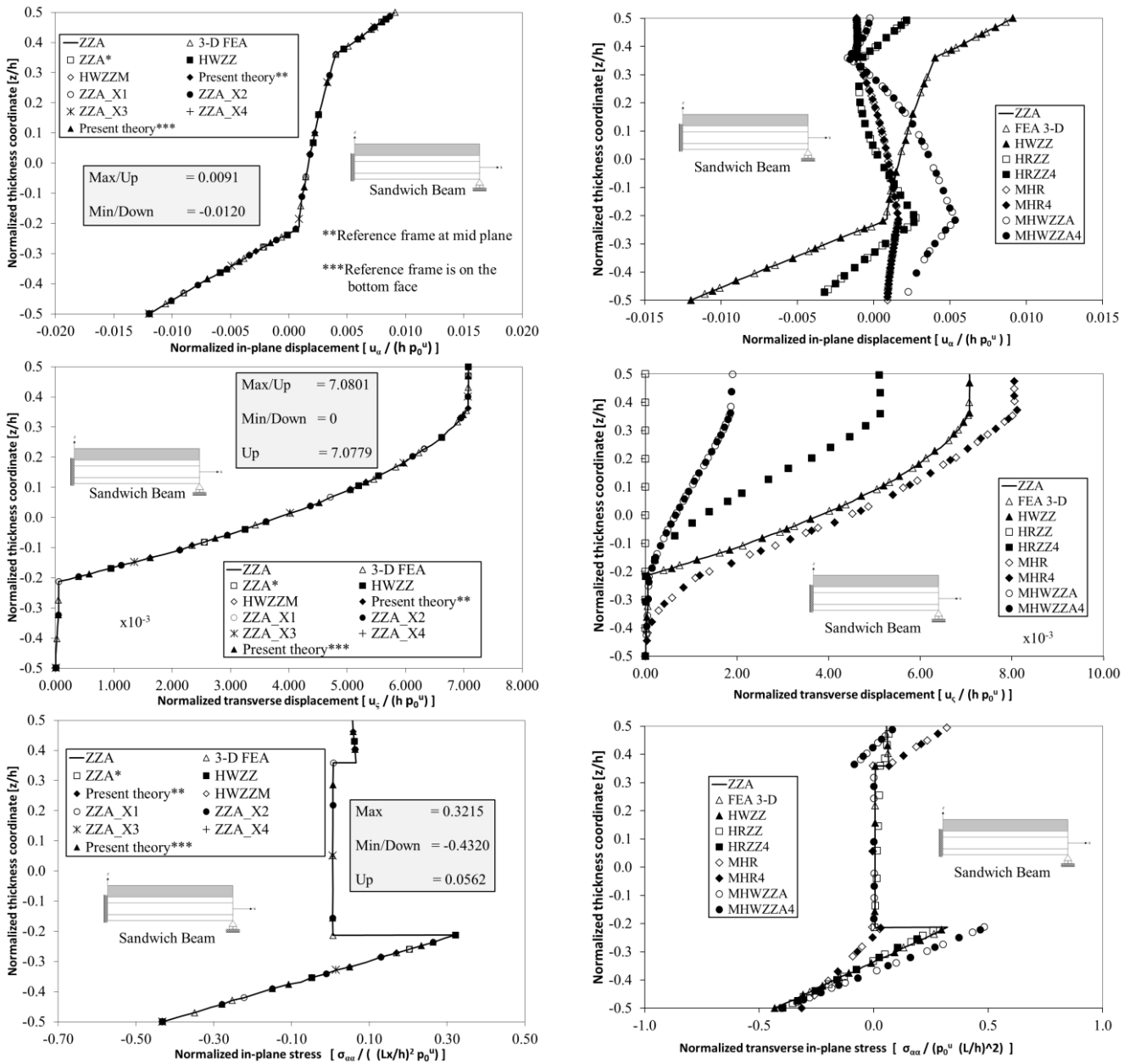
3.1 Case A

This case concerns a propped cantilever sandwich beam under a uniform transverse loading applied on its upper face, i.e. whose edges are clamped at $x=0$ and supported at $x=L$ at the bottom layer, having a length-to-thickness ratio of 14.268. Nevertheless this case is not extremely thick, as instead usually considered when testing theories in order to boost 3-D effects, strong layerwise effects occur because of its material properties and loading and boundary conditions, as evidenced also by the results of theories HRZZ, HRZZ4, MHWZZA, MHWZZA4, MHR and MHR4 reported in [21], in comparison to the higher order theory ZZA [19], which are all together reported in this paper for demonstration purposes.

HRZZ and HRZZ4 are two mixed HR physically-based theories whose in-plane displacement is the same of ZZA, while transverse one is uniform and fourth-order polynomial respectively (stresses apart from local equilibrium equations). MHR

and MHR4 are two kinematic-based theories that include Murakami’s zig-zag function into in-plane displacement, while transverse one is fourth-order and piecewise polynomial respectively. Instead, MHWZZA and MHWZZA4 has the same displacement field of MHR (MHWZZA4 has also the same transverse displacement of ZZA), while strains and stresses are retaken from HWZZ. The latter theory is a mixed HW (strains and stresses assumed independently from kinematics) physically-based adaptive zig-zag theory, whose coefficients, differently to previous theories, are redefined for each layer across the thickness by imposing the full set of physical constraints (2) to (5).

As shown by Figure 2, a large dispersion of results is highlighted for in-plane and transverse displacements, the cause being the still too poor kinematics of HRZZ to MHR compared to ZZA, the latter having a redefinition of coefficients similar to that of the present theory, from which it differs only in the fact it still adopts a model across the thickness, which although it is very general it is still predefined a priori. Because of their shortcomings, theories HRZZ to MHR incorrectly predict transverse shear and normal through-thickness stress fields in the most critical region considered, as compared to 3-D FEA results (whose degree of accuracy will be highlighted below). On the contrary ZZA and the present approximate 3-D solution show results in agreement with each other and with 3-D FEA for all quantities and everywhere.



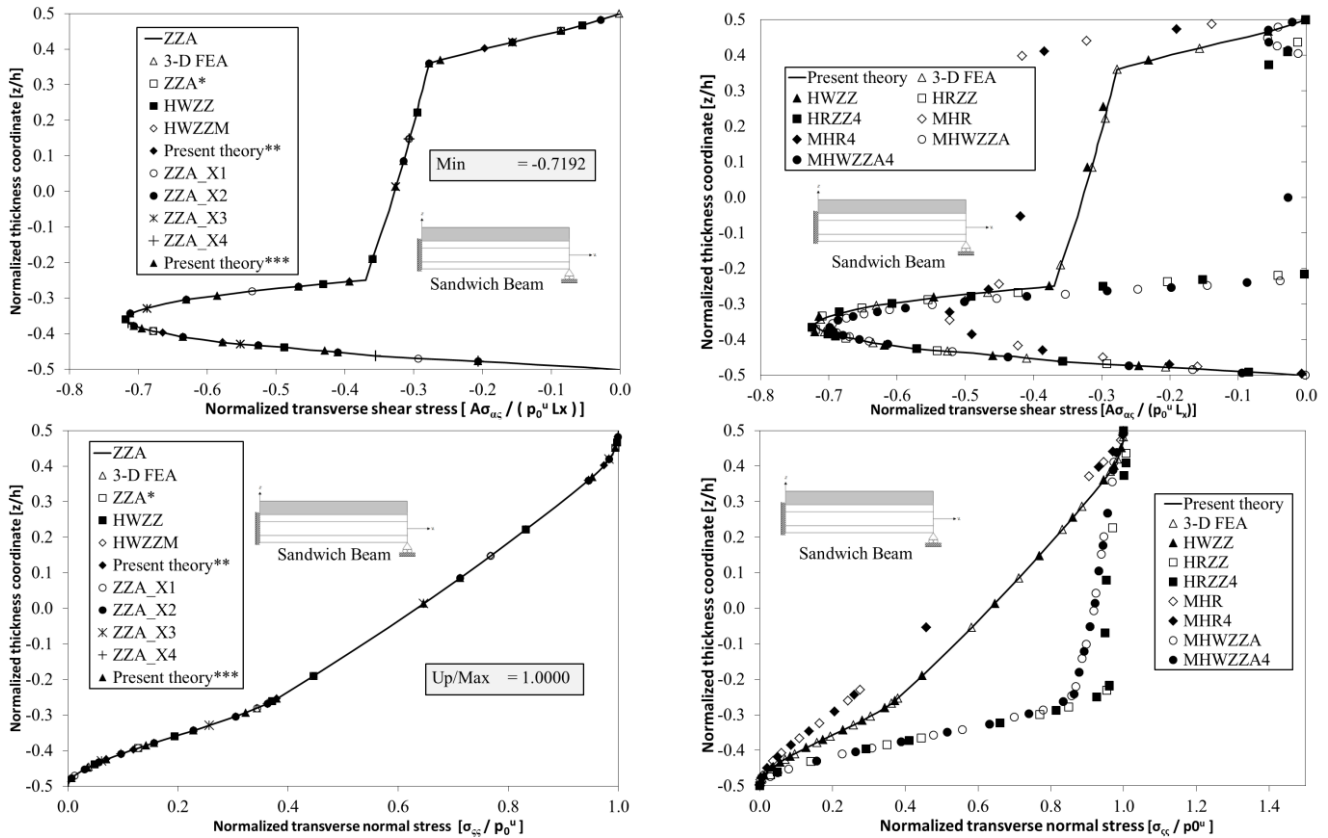


FIGURE 2: Case a: Normalized displacements and stresses, propped cantilever sandwich beam under a uniform loading.

The figure also shows the values assumed by the present theory at the top (Up) and bottom (Down) of the laminate and the maximum (Max) and minimum (Min) values across the thickness.

In addition to demonstrating the accuracy and efficiency (see Table 4 giving the processing time) of the present approximate 3-D solution search procedure, the results of Figure 2 also offer the possibility to comment on the requirements that the theories should have to accurately capture all the 3-D effects that are relevant.

**TABLE 4
COMPUTATIONAL EFFORT [S] FOR THE EXAMINED CASES AND THEORIES.**

	Theory	a	b	Case c	d	e	f
	FSDT	4.0338	2.2857	4.0928	1.8971	7.2570	4.0293
(arbitrary representation)	Present theory	13.1075	4.1127	8.6521	4.2235	16.2312	9.0803
	ZZA_X1	11.9180	3.7531	7.9473	3.8206	14.7913	8.1602
	ZZA_X2	12.2758	3.8442	8.0691	3.9522	15.1387	8.4179
	ZZA_X3	12.3912	3.8573	8.2443	4.0019	15.4243	8.5103
	ZZA_X4	12.5271	3.8553	8.1855	3.9869	15.3804	8.4476
Mixed HW	HWZZ	12.7078	4.4355	6.4151	5.1020	15.3278	6.6966
(Murakami's zigzag u^3, v^3, w^4) (adaptive)	HWZZM	12.7083	3.9657	8.4218	4.0728	15.7581	8.7583
(no zig-zag functions u^3, v^3, w^4)	ZZA	15.7617	4.9446	10.4055	5.0946	19.4522	10.8600
	ZZA*	11.8971	3.6656	7.7602	3.7789	14.6491	8.1071

Computer with quad-core CPU@2.60GHz, 64-bit OS and 8.00 GB RAM. Processing time is defined apart from the symbolic procedure used to create the model (which takes less than 10 seconds).

Nevertheless Murakami's rule is respected; theories MHR, MHR4, MHWZZA and MHWZZA4 using Murakami's zig-zag function provide very inaccurate results which demonstrate that physically-based theories HRZZ, HRZZ4 and ZZA, whose zig-zag amplitudes are recalculated at layer interfaces by enforcing stress compatibility conditions (2) like for the present approximate solution approach, are ones suitable for analysis. Findings of Figure 2 also show that an accurate description of transverse displacement is mandatory for the present case a, since HRZZ and HRZZ4 (that assume a uniform and a polynomial representation for u_z , while in-plane displacement is piecewise polynomial) cannot reach the same precision of the present theory, ZZA, HWZZ, ZZA*, HWZZM [20], ZZA_X1 to ZZA_X4 [26], which have coefficients that are redefined across the thickness as common feature. It should be noticed that two different reference frames are assumed for the present theories (the first one is assumed at the middle plane of plate, while the second one is assumed coincident with the bottom face of plate). Particularly, HWZZM is a mixed physically-based HW theory that includes Murakami's zig-zag function and a second order zig-zag one are used instead of ZZA ones; strains and stresses are assumed apart like in HWZZ. Zig-zag functions are omitted in ZZA* while different representations (than power series of z) of transverse variation from point to point for each displacement are assumed for ZZA_X1 to ZZA_X4. Because of the results of these latter cited theories ZZA to ZZA_X4 and ones by the present 3-D approximate solution procedure are indistinguishable from each other, it is demonstrated that the choice of zig-zag and representation functions is immaterial, if coefficients are redefined for each layer so that the full set of physical constraints (2) to (5) is imposed. Because, as shown in [21] in a broader way from the point of view of the cases examined, all theories that only partially satisfy (2) to (5) give results that depends on the choices made for zig-zag and representation functions and whose accuracy degree results strongly case-sensitive, none of them is worthy of being used for comparisons with the present 3-D solution, nor for use in the analyses. Table 4 shows the processing time of the present approximate 3-D approach and those of theories ZZA, ZZA*, HWZZ, HWZZM, ZZA_X1 to ZZA_X4. The computational effort of other theories is not reported, but they are similar to those of previous ones, which are still comparable to those of ESL [21]. Because of HRZZ, HRZZ4, MHWZZA, MHWZZA4, MHR and MHR4 are less accurate than the present theory, ZZA, ZZA*, HWZZ, HWZZM, ZZA_X1 to ZZA_X4, they will not be reported for the following cases.

Apart from the comments on the behavior of the various theories, on the basis of their approximations, it is evident that the proposed approach is accurate and therefore can be used profitably as a reference solution when the exact one is not available.

3.2 Cases B and C

Case b is a [0/90/0] multilayered simply-supported beam under a sinusoidal loading, whose constituent layers are made of the same material. This case is considered, although it is not particularly severe from the standpoint of layerwise effects, given the existence of the exact solution that lends itself suitable both to assess the accuracy of this procedure, and simultaneously that of 3-D FEA.

Results provided by the present solution methodology those by 3-D FEA and ones by ZZA, ZZA*, HWZZ, HWZZM, ZZA_X1 to ZZA_X4 are compared to the exact solution by Pagano retaken from [17], as shown in Figure 3. It is shown that all theories considered in this figure are able to accurately predict displacements and stresses, their results being very close to exact solutions. Since the theories considered are based on different assumptions as regards the functions that characterize the representation across the thickness as well as zig-zag functions, the uniformity of the results shows that also in this case it can be argued that the choice of zig-zag function and of the representation form can be freely chosen, with the former that even be omitted if coefficient of theories are recalculated for each layer through the enforcement of (2) to (5). Anyway, the results show that the present 3-D approximate solution approach and 3-D FEA provide very accurate results compared to exact solution, therefore they lend themselves to be used as comparison solutions in the cases in which arbitrary lay-ups, loading and boundary conditions are considered. Like the previous cases, Table 4 shows the processing time of all theories that are always comparable to those of ESL.

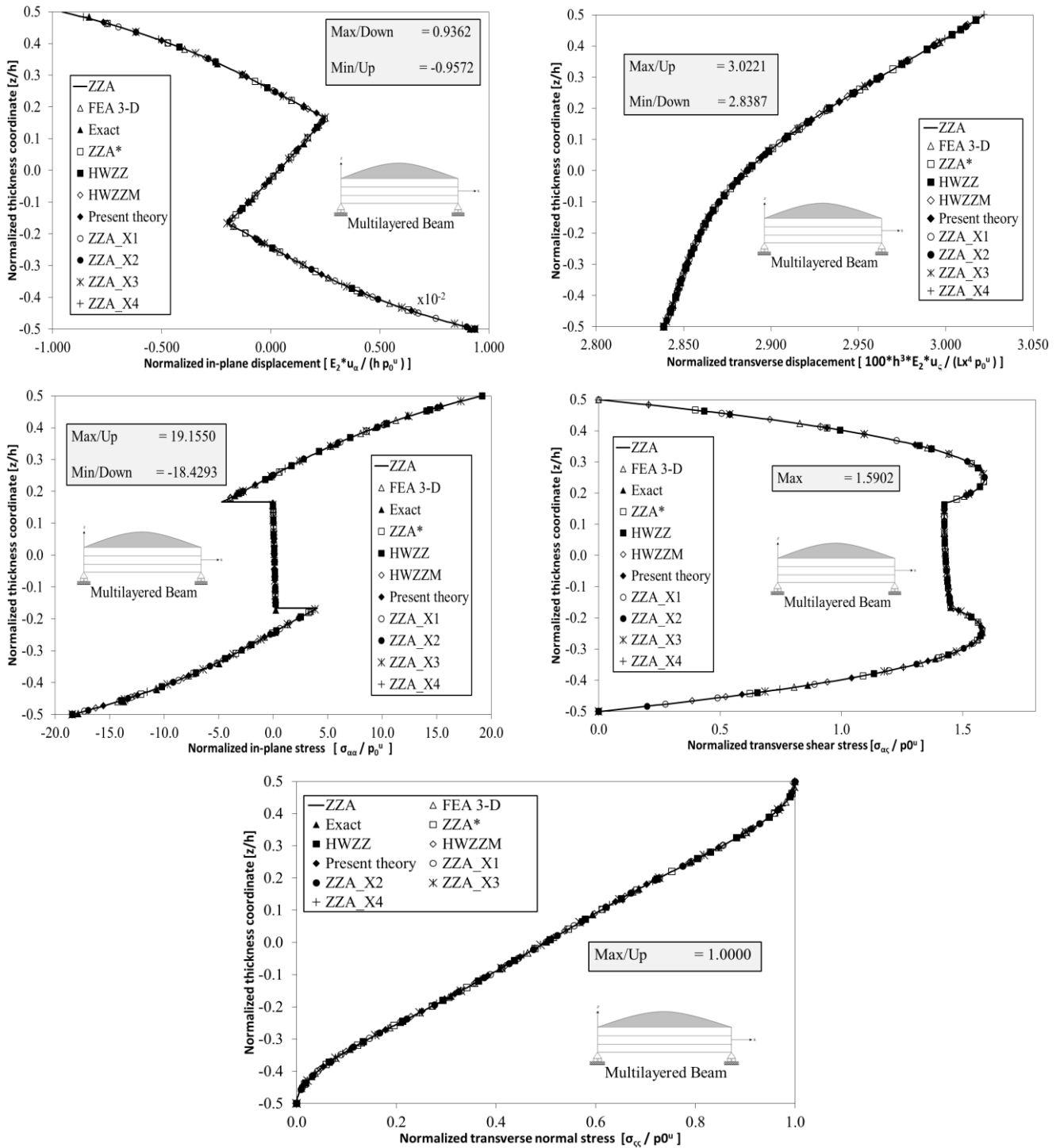


FIGURE 3: Case b: Normalized displacements and stresses, simply-supported laminated beam under a sinusoidal loading.

Regarding case c (Figure 4), it is a simply-supported rectangular sandwich plate, previously studied by Brischetto et al. [27]. Faces have different thickness and are made of different materials and results provided by ZZA, ZZA*, HWZZ, HWZZM, ZZA_X1 to ZZA_X4 and 3-D FEA are compared to exact ones. Indistinguishable results are obtained by previously cited theories, so, the same considerations of cases a and b still apply.

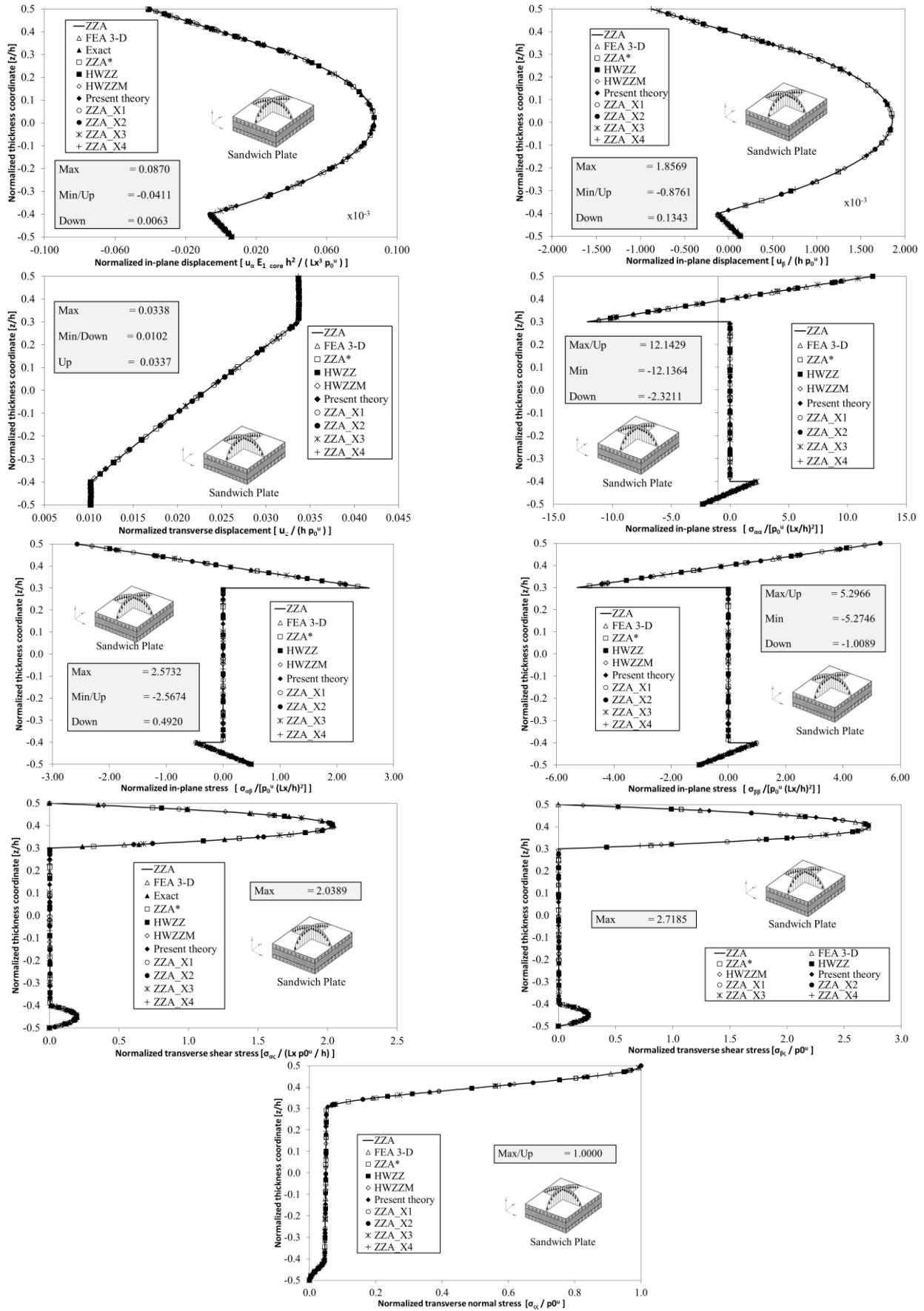


FIGURE 4: Case c: Normalized displacements and stresses, simply-supported rectangular sandwich plate under a bi-sinusoidal loading.

Nevertheless results of cases b and c have demonstrated the high-accuracy of the present solution procedure, further benchmarks with localized loading or damaged layers have to be considered to state with certainty that it and 3-D FEA as well can be used as comparison solutions in cases whenever the exact solution is not available.

Also in these cases, the present approximate 3-D solution approach appears accurate and then valuable as a reference solution.

3.3 Cases D, E and F

In order to comply with the need expressed in the previous sentence at the end of the previous section, three kinds of simply supported beams and plates are considered, whose displacement and stress fields are difficult to capture because of their strong layerwise effects due to the types of loading considered, which do not admit exact solution despite the constraints are those less burdensome in terms of modeling.

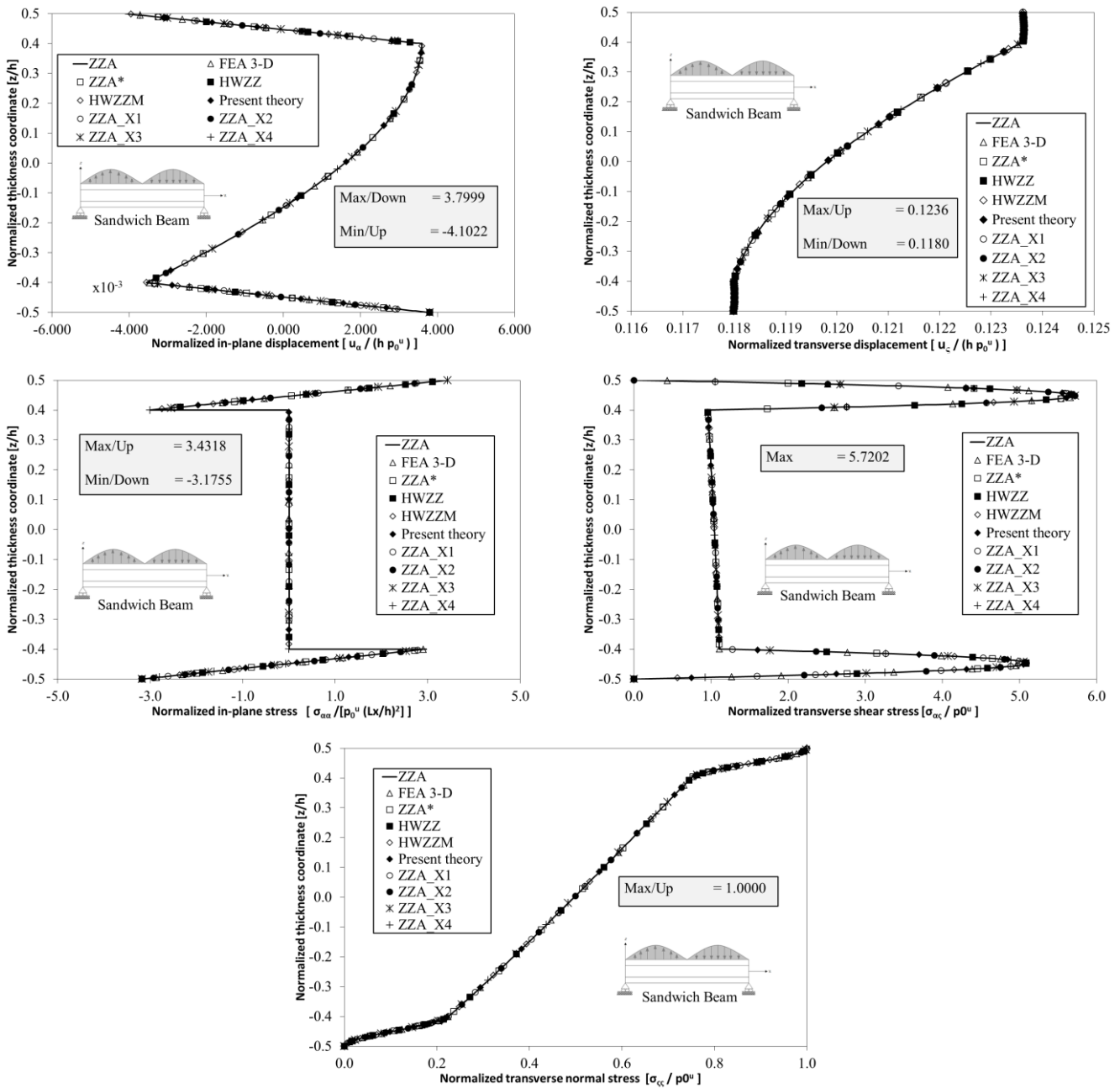


FIGURE 5: Case d: Normalized displacements and stresses, simply-supported sandwich beam under a sinusoidal loading (two half-waves).

Case d (Figure 5) is a simply-supported sandwich beam under a two half waves sinusoidal loading on the upper face, case e (Figure 6) is a simply-supported laminated beam under a uniform loading applied on the same face for $x \leq Lx/2$ and on the lower one for $x > Lx/2$ having an opposite sign. Case f (Figure 7) is a simply-supported sandwich rectangular plate (length-to-thickness and length-to-side ratios are 4 and 3 respectively), under a bi-sinusoidal loading and with the lower face damaged (elastic modulus E_{1111} , E_{1122} , E_{2222} , E_{1212} of the first layer from below are reduced by a factor of $2 \cdot 10^{-1}$). This latter case is considered because this condition can occur during the service life, for example as a result of impact damage. Anyway, all these cases represent severe tests for models and for this region they are chosen. They show an asymmetric behavior across the thickness, either because of their lay-ups, material properties or loading conditions.

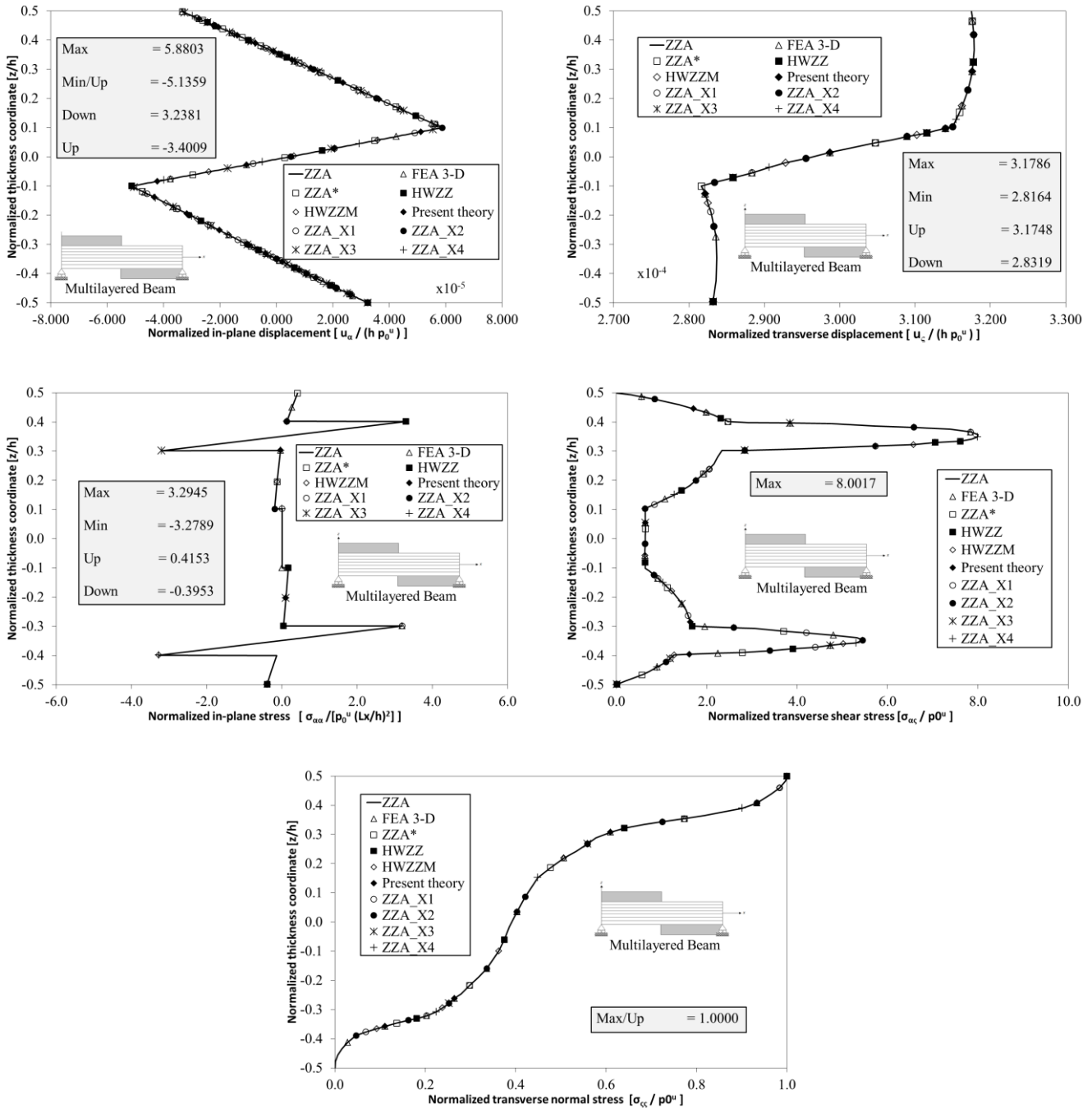
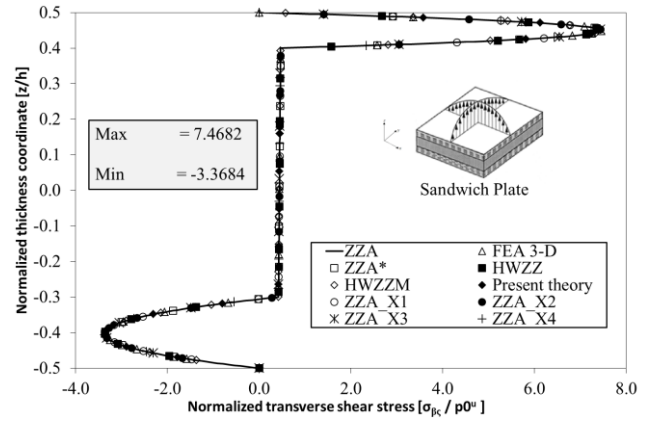
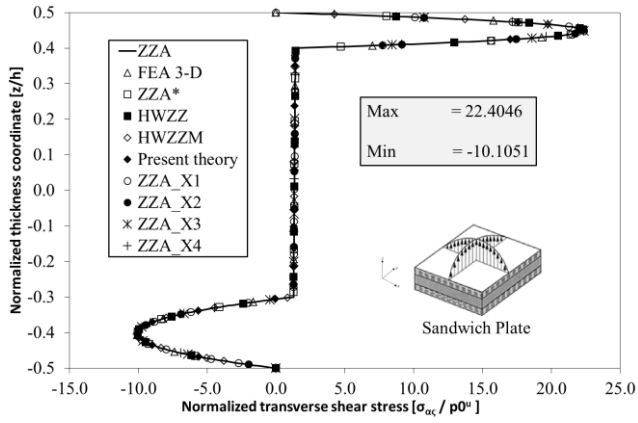
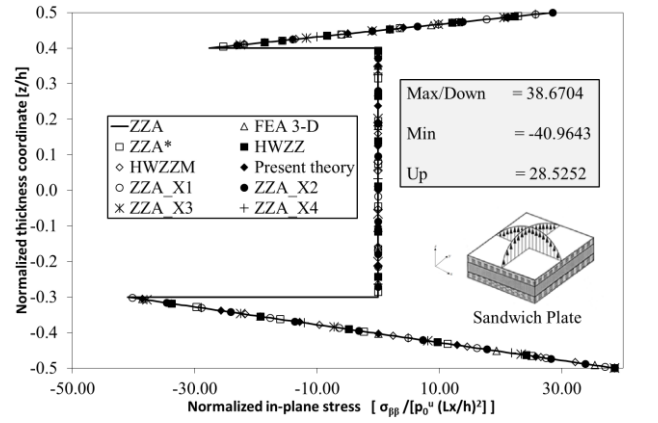
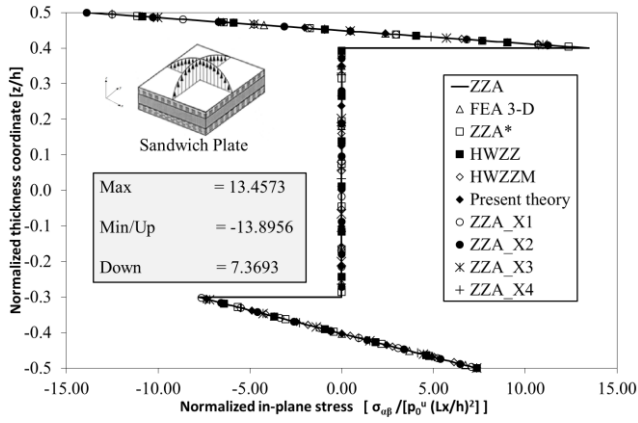
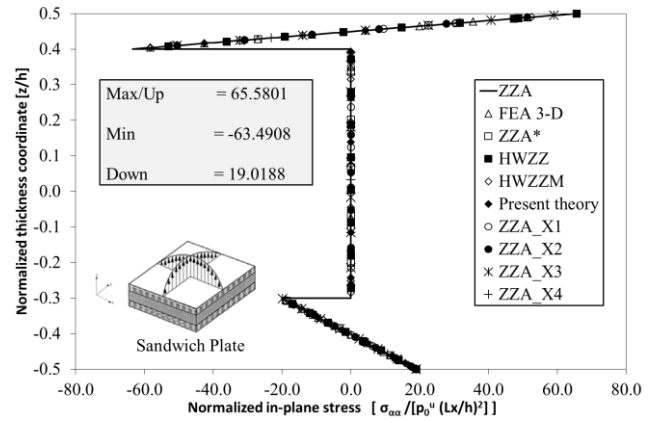
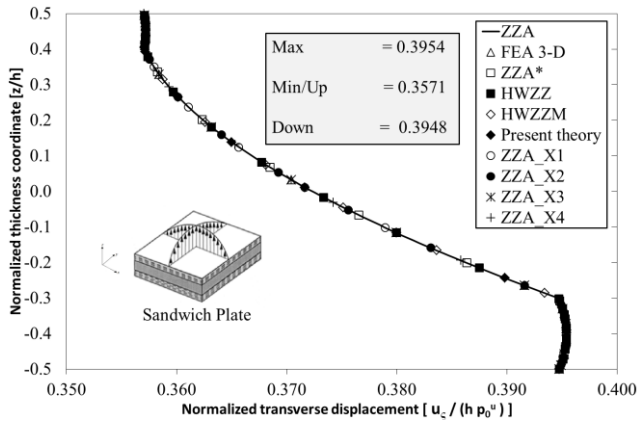
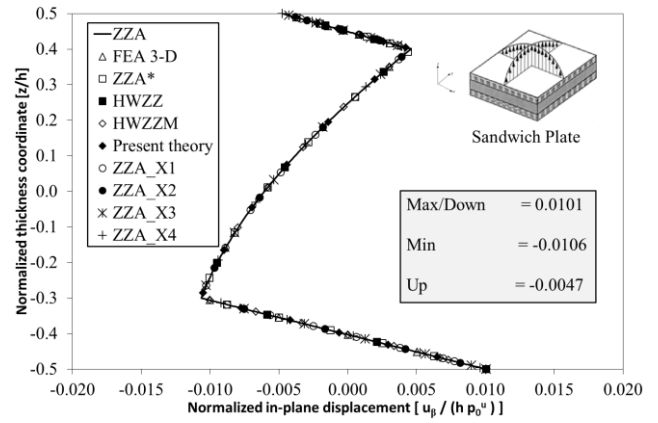
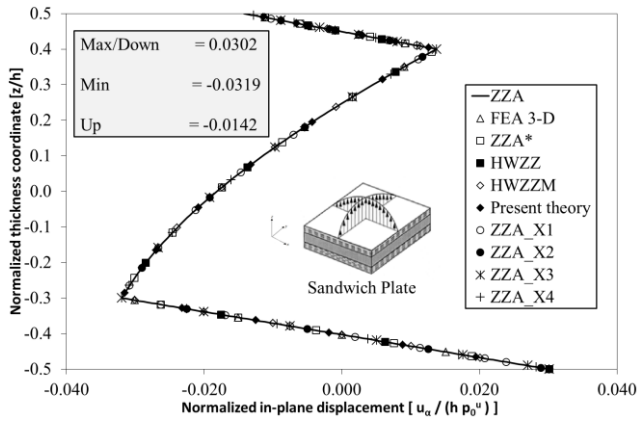


FIGURE 6: Case e: Normalized displacements and stresses, simply-supported laminated beam under localized step loading.



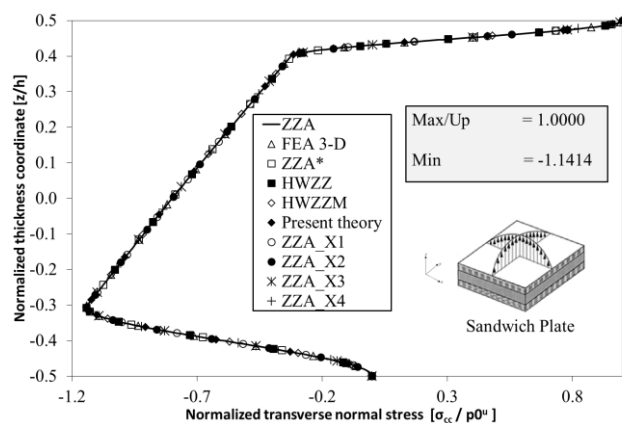


FIGURE 7: Case f: Normalized displacements and stresses, simply-supported rectangular sandwich plate under a bi-sinusoidal loading. The lower face is damaged by a factor of $2 \cdot 10^{-1}$.

The results by the present approximate 3-D solution approach and the ones by the theories already mentioned above, which recall its characteristics due to the fact that coefficients are redefined across the thickness, although they are based on different assumptions from each other, are compared to the results of 3-D FEA, as done previously.

For cases d and e, in-plane displacement and transverse shear stress are shown at $x=0$, while the other quantities (transverse displacement, in-plane and transverse normal stresses) are shown at $x/L_x=0.25$.

It can be seen that the present approximate solution approach and those of theories ZZA , ZZA^* , $HWZZ$, $HWZZM$ and ZZA_X1 to ZZA_X4 , whose coefficients are redefined for each mathematical or physical layers through the enforcement of the full set of physical constraints (2) to (5) are equally accurate, their results being very close to those of 3-D FEA.

The results of other theories considered in [21], here not reported so as not to complicate the graphics too much, on the contrary show discrepancies that indicate their lower predictive capability, also in virtue of a partial satisfaction of constraints, which results in a strong dependence of the assumptions made concerning the type of representation and the zigzag functions chosen. Table 4 shows once again and for the present cases that the processing time of all theories is still always comparable to that of ESL although to their accuracy it is much higher, therefore in fact attesting to their efficiency. Again, the present approximate 3-D solution approach proves to be efficient, accurate and suitable as a reference solution.

IV. CONCLUDING REMARKS

A 3-D approximate solution procedure has been proposed in this paper which avoids assuming any restrictive hypotheses across the thickness about through-thickness kinematics, strain and stress fields, like on the contrary usually done for developing laminated plate theories so to overcome algebraic difficulties.

A general representation of variables is assumed, which is based on a fixed number of unknowns irrespective for the number of constituent layers, whose intended aim is to capture all the salient three-dimensional effects with a low computational cost, so to provide a quick and accurate tool that provides a reference results for cases where exact solutions cannot be found with the known techniques, due to the considered lay-up, loading and boundary conditions.

It comes to constitute a generalization of zig-zag theories [19-21], which likewise uses a fixed number of d.o.f. irrespective of the number of layers, for the ideas on the basis of which it is developed. The fundamental aspect to underline is the lack of zig-zag layerwise functions, as the coefficients of the displacement field play themselves the role of layerwise functions being redefined across the thickness through the enforcement of physical constraints related to out-of-plane compatibility of stress components, displacements and fulfillment of stress-boundary conditions.

The characteristic feature that enables the development of such a general physically-based theory is that all constraints are satisfied in exact form through use of a symbolic calculus tool that provides once and for all expressions deriving from the enforcement of constraints. An analytical solution is searched as a truncated expansion series of trial functions and unknown amplitudes using Rayleigh-Ritz and Lagrange multipliers methods.

To assess its accuracy, a number of challenging benchmarks with strong layerwise effects have been considered, along with applications with less demanding characteristics from the standpoint of modeling, for which exact solutions are available.

The results of all these applications show that invariably the present approximate 3-D solution turns out to be accurate and of low cost, as shown by the comparison with the exact results when available and the results of 3-D FEA and by recent laminated plate theories by the authors, which although presenting similar characteristics as the lack of explicit zigzag functions and the imposition of strict constraints across the thickness are however based on a priori assumptions

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