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Methodology for composite materials shrinkage definition for use in shipbuilding and marine technology

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ABSTRACT

Deformations of steel material in shipbuilding and marine technology applications as a result of mechanical or temperature influences are a well-known problem. However, in the modern shipbuilding industry, the application of alternative materials, especially composite materials, in the structure and for the equipment of the ship is increasingly represented. Consequently, there is a need to determine the deformation and change of characteristics of such composite materials as a result of various mechanical, and especially temperature influences that cause the so-called shrinkage. The basic composite production process involves connecting the matrix with a catalyst and accelerators that create temperature, then the material shrinks by cooling when it can change its dimensions and characteristics. Also, in order to achieve the best possible mechanical properties, composite materials are specially heated and then cooled according to strictly defined processes and curves. The ability to predict the characteristics and parameters of such deformations is important in the context of the application of composite materials. To define such deformations, different methods are used within individual numerical solvers, whose results can differ significantly from each other. Therefore, the authors in this paper present an established methodology for predicting mechanical and temperature deformations, and modelling of composite materials, based on the analysis of analytical methods and numerical solvers with the aim of defining the most accurate numerical solver. By applying the presented methodology, it is expected to raise the level of accuracy and quality of composite materials production as well as to raise the quality of design solutions and efficiency of production procedures during shipbuilding in particular, but also within different marine technology applications and during the product's life cycle.

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1 Introduction

Deformations of steel material in shipbuilding and marine technology applications are a well-known and researched problem, [1]. Deformations of steel material in the shipbuilding process occur primarily as a result of mechanical influences due to the manipulation of the product in the process [2] and temperature influences as a result of processing and welding the steel structure and equipment, the so-called shrinkage, [3] and [4]. However, the application of alternative materials, especially composite materials, in modern shipbuilding engineering and marine technology is increasingly represented, [5].

Composite materials usually include a combination of resin (matrix) and reinforcement (fibre) and the benefits of the application of composite materials in the field of shipbuilding, marine technology and marine structures have been researched and documented, [5], [6]. In particular, the advantages of composite materials in the area of structure are primarily their lower mass, [7], which consequently allows lighter structures, [8] and corrosion resistance, [9]. Furthermore, composite materials are also used in the field of ship equipment, [4], [10], [11], and they also play an important role within the research of new adaptive and smart materials, [12].

In the production of composites, the basic process involves the connection of the matrix with the catalyst and accelerators that create temperature, and then the material shrinks by cooling, and at the same time it changes its characteristics, [13]. In addition, mechanical properties of

some composite materials can be enhanced by controlled introduction of heat into the finished composite part and then cooling the part to reach the room temperature, usually according to the resin manufacturer's specification. This procedure becomes even more significant with large dimensions of composite panels, which have been one of the most frequent applications of composites in shipbuilding in recent years, for decks and plates of large composite panels in cargo space or superstructure, [14], primarily to reduce mass and to achieve a more favourable position of the centre of gravity, [15]. Such composite panels are usually made outside the shipyard, and are installed on the ship on a pre-constructed structure during the ship assembly. It is clear that in such a case, the accuracy of construction and precision of dimensions, knowing the deformations in the manufacture of composite panels, is of great importance because the opposite can lead to significant disruptions in the production process. Consequently, the authors point to the need for analysis, testing and determination of deformations of such composite materials as a result of various mechanical and especially temperature influences. Namely, the ability to predict the characteristics and parameters of such deformations is important in the context of the application of composite materials, i.e. increasing the level of product quality in the production of composites and in the process of ship design and construction while also improving collaboration with material and equipment manufacturers.

Various experimental methods [16], [17], [18], methods based on mathematical modelling [19] and methods based on the application of numerical solvers [13], [20], [21] are used to define such deformations. However, according to the authors' observations, the settings and results of different numerical solvers for the same or similar case may differ significantly from each other. Therefore, the authors in this paper present an established methodology for determining mechanical and temperature deformations and modelling the composite materials. This methodology is based on the analysis of analytical methods and numerical solvers with the aim of selecting the most accurate numerical solver. The presented methodology is in the first part based on the comparison of the results obtained by analytical calculation with the results obtained in two different finite element solver methods for the purpose of verification of results or selection of solvers with the smallest deviation from the confirmed analytical method. Furthermore, the settings thus obtained were then applied to define and model the composite material and its thermal expansion through the example of cooling the composite plate from the production temperature to room temperature. It is expected to raise the level of accuracy of the design solution as well as the quality of composite materials production and the efficiency of production procedures during shipbuilding in particular by applying the methodology presented in the article.

2 Determination of the reference values

To set the reference values for modelling of the composite materials, as well as the thermal component of the problem, a simple analytical model will be presented. Some of the ply properties for E-glass/epoxy fibre and matrix combination were taken from literature [22] and presented in Table 1.

As for the structural part of the calculation, the results for the deflection of the composite plate, with 20 kPa of pressure applied to the upper surface of the plate, were calculated (as described in [22]). The plate is 1.6 m in length and has a width of 0.5 m. The composite layup of sixteen layers was placed in $[0/90/+45/-45]_{2S}$ direction, thus making the laminate symmetrical around the neutral axis. The thickness of each layer is 1 mm, giving the 16 mm in total thickness of a composite plate. It is a quasi-isotropic layup, designed to eliminate [**B**] matrix component in **A-B-D** matrix ([**B**] = 0) and also intended to get as close as possible to the isotropic plate expressions for matrix [**A**] and [**D**] which is shown in:

Table 1 Properties of E-glass/epoxy laminate [22]

Property	Values		
Density	ρ	[g/cm^3]	2.076
Longitudinal Modulus of Elasticity	E_1	[GPa]	45
Transverse Modulus	E_2	[GPa]	12
In-Plane Shear Modulus	G_{12}	[GPa]	5.5
In-Plane Poisson's Ratio	ν_{12}		0.19
Transverse Poisson's Ratio	ν_{23}		0.31
Longitudinal CTE*	α_1	[10^{-6}/°C]	3.7
Transverse CTE*	α_2	[10^{-6}/°C]	30
Longitudinal Moisture Expansion	β_1		0
Transverse Moisture Expansion	β_2		0.2
Fibre Volume Fraction	V_f		0.6

*CTE – coefficient of thermal expansion

$$[\mathbf{A}] = \frac{Et}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \quad (1)$$

$$[\mathbf{D}] = \frac{Et^3}{12(1-\nu^2)}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \quad (2)$$

where E is laminate equivalent Young's modulus, t is laminate overall thickness and ν is equivalent Poisson's ratio. These equations can, according to [22], be used as a reasonable approximation with the quasi-isotropic stacking sequence and a large number of laminae.

This can be verified, by using the classical laminate plate theory (CLPT) and combining the values from Table 1 and the stacking sequence $[0/90/+45/-45]_{2S.}$ Then the bending stiffness matrix calculated by CLPT is:

$$[\mathbf{D}] = \begin{bmatrix} 9.66 & 1.61 & 0.2 \\ & 8.33 & 0.2 \\ sym. & & 2.7 \end{bmatrix} 10^{-3}\ MPa\ m^3$$

where $D_{11} \approx D_{22}$ and $D_{16} >> D_{11}$.

The deflection can be calculated using the Navier method [22] for a simply supported plate:

$$W_{mn} = \frac{16pb^4}{\pi^6 mn\left(D_{11}m^4\frac{b^4}{a^4} + 2(D_{12}+2D_{66})m^2n^2\frac{b^2}{a^2} + D_{22}n^4\right)} \quad (3)$$

where m=n=1, p is the pressure applied on the plate, b is the shorter dimension of the plate, a is the longer dimension of the plate and D_{11}, D_{12}, D_{66} and D_{22} are elements of bending stiffness matrix.

Therefore, maximum deflection can be calculated for the current scenario w_{max} = 10.97 mm. Similarly, stress can also be computed using the laminate theory. The stress values are given in Table 2.

As for the thermal part of the validation process, the elongation (or shrinkage in particular case) of the material under the thermal load will be considered. The E-glass/epoxy plate from the previously described mechanical problem was heated to the temperature of 80 °C (i.e. in post-curing process). The plate was then air cooled up to 20 °C.

The shrinkage of the plate needed to be calculated using a simplified method described below. For any uniaxial load this change in length ΔL can be considered as elongation due to the mechanical load, change in temperature and change in moisture level. This can be written using the equation [22]:

$$\Delta L = (\varepsilon + \beta\Delta m + \alpha\Delta T)L_0 \quad (4)$$

where ε is mechanical strain, β is coefficient of moisture expansion, Δm is the change in moisture concentration, ΔT is the change in temperature, and α is the coefficient of thermal expansion (CTE). For the given problem, the moisture expansion will be neglected.

Composites usually have two coefficients of thermal expansion. Thus, considering the single composite ply, one CTE is calculated in fibre direction of the composite ply and the other is calculated perpendicularly to the fibre direction. This can be achieved using equations (5) in the direction of fibres, taken from literature [23]:

$$\alpha_1 = \frac{\alpha_A V_f E_A + \alpha_m V_m E_m}{E_1} \quad (5)$$

and in the direction perpendicular to the fibres using equation (6) from the literature [23]:

$$\alpha_2 = \alpha_3 = \alpha_T\sqrt{V_f} + \left(1-\sqrt{V_f}\right)\left(1 + V_f\nu_m\frac{E_A}{E_1}\right)\alpha_m \quad (6)$$

where E_1 is the Young's modulus of the ply in the fibre direction, E_A is the Young's modulus of the dry fibre in the fibre direction, E_m is the Young's modulus of the matrix, ν_m is the matrix Poisson's ratio, V_f is the fibre volume fraction, V_m is the matrix volume fraction, α_A and α_T are CTE of dry fibre in fibre direction and perpendicular to fibre direction respectively, while α_m is the CTE of matrix.

The above mentioned CTE values are calculated and presented in the Table 1 for the observed ply. These values can be directly inserted as material properties of a single ply when working with some finite element analysis software (i.e. in FEMAP). However, in some cases an equivalent coefficient needs to be calculated as the coefficient which takes into account the laminate as one part (i.e. when using LS-DYNA). Since the laminate described in the analytical problem is isotropic in the plane of the ply, the equivalent CTE can be calculated using the equation for randomly oriented fibres [22]:

$$\alpha_q = \frac{\alpha_1+\alpha_2}{2} + \frac{\alpha_1-\alpha_2}{2}\cdot\frac{E_1-E_2}{E_1+(1+2\nu_{12})E_2} \quad (7)$$

where α_1, α_2, E_1 are described in the text above and E_2 is the Young's modulus of the ply perpendicular to the fibre direction and ν_{12} is the in-plane Poisson's ratio. For the given composite, the equivalent CTE can be easily calculated,

Table 2 Reference values for E-glass/epoxy laminate – results

Model type	w_{max} [mm]	σ_{bm} [MPa]	σ_{am} [MPa]	ΔL_{long} [mm]
Reference values	10.97	18.0	19.4	0.9408

Source: Authors

giving the value of the coefficient α_q = 9.8×10^{-6}/K for both directions of the laminate.

Using the equation (4), the total shrinkage in the longitudinal direction of the plate can be calculated, completing the table for reference values. The results are presented in Table 2 alongside with data (results) for deflection and stress which are a solid starting point for FEA (Finite Element Analysis) software evaluation and calibration. Referring to Table 2, w_{max} represents maximum deflection, σ_{bm} is the calculated maximum stress in shorter panel dimension, σ_{am} is the calculated maximum stress in longer panel dimension and ΔL_{long} is the shrinkage in longer panel dimension for calculated ΔT=60 °C.

3 Finite element software evaluation

For the software evaluation LS-DYNA R11.1 and FEMAP 2020.2 were chosen. Both of these computer programmes have the possibility of applying composite properties to shell elements and they are also capable of conducting the thermal analysis of composite materials. FEMAP is a Nastran based programme and LS-DYNA uses its own solver. Both of these computer programmes are in engineering use in shipbuilding, mechanical engineering and automotive industry, as well as in other fields of engineering (i.e. aeronautical and civil engineering). However, the evaluation method described in this chapter can also be used on any type of software capable of structural calculation with the composite material.

To evaluate the software, the model of the plate needs to be created and meshed with shell elements. The size of the elements chosen for the purpose was set to 20 mm, using the quadratic elements with aspect ratio of a/b =1. The composite materials property should be taken from the baseline values described in previous chapter. These data should be sufficient for most up-to-date FEA software. The detailed method of model creation and property input should be checked with the particular software user manual. For the described problem, directions from the literature [24], [25] were taken. However, it should be noted that the thermal solver for LS-DYNA was triggered through the separate control card in order to calculate the shrinkage (in accordance with the user manual). The boundary conditions for the structural part should be defined and placed on the edges of the composite plate. The pinned condition needs to be used, preventing translation in x, y and z direction. The pressure of 20 kPa should be applied to the upper surface of the plate.

For the calculation of the thermal expansion, the recommendation is to constrain x and z direction on two nodes located at the far corners of the plate (designation 13 shown in Figure 1), while constraining the y and z directions in the node at the centreline of the plate (designation 23 shown in Figure 1). The laminate layup is symmetrical, therefore the deflection in z direction will be zero or close to zero. The temperature change should be set from 80 °C to 20 °C according to the problem description.

These described problems are fairly simple to create in any FEA software and the calculation time is measured in seconds. In comparison to LS-DYNA, FEMAP was able to plot out properties of the laminate layup and verifying the bending stiffness matrix calculated in the example and one extracted from FEMAP are identical. The final results for the structural part of the problem are extracted from FEMAP and LS-DYNA and the deflection of the composite plate was presented in Figure 2 and Figure 3. The values

Figure 1 Boundary conditions for calculation of thermal expansion FEMAP interface presented

Source: Authors

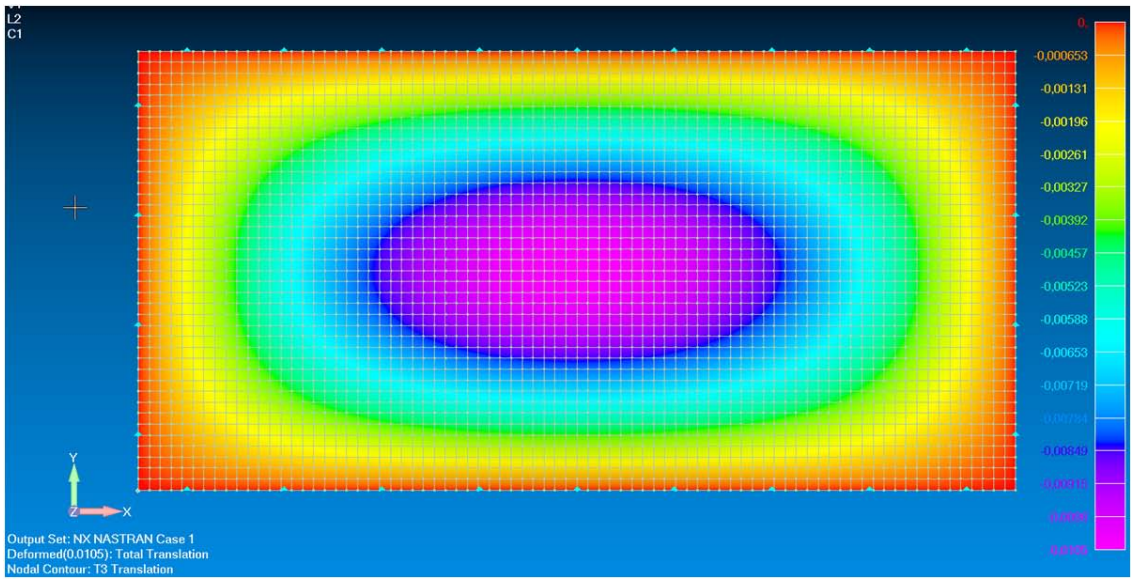

Figure 2 Deflection of the composite plate pinned on all edges (FEMAP)

Source: Authors

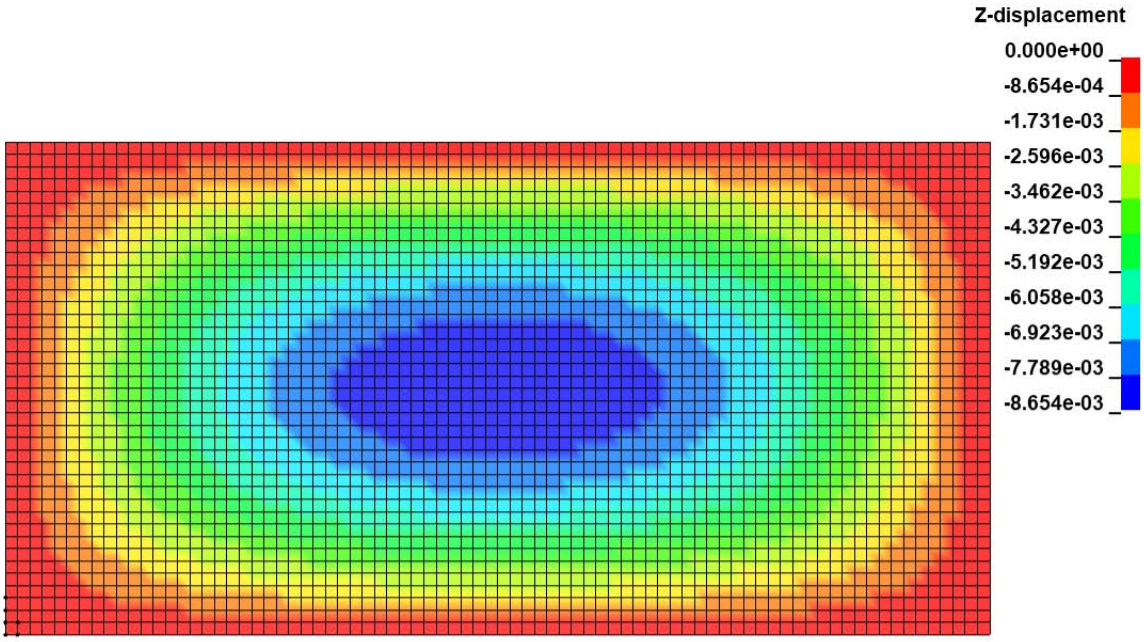

Figure 3 Deflection of the composite plate pinned on all edges (LS-DYNA)

Source: Authors

shown in figures are in meters and the maximum deflection for the pinned plate is expected at the center of the plate. The calculated deflection using FEMAP is 10.5 mm and for LS-DYNA software the deflection is rounded to 8.66 mm.

The input values of the CTE differed for FEMAP and LS-DYNA. While FEMAP allowed direct input of α_1 and α_2, for LS-DYNA an equivalent CTE needed to be calculated using the equation (7). Results for the shrinkage in longitudinal (longer) and transversal (shorter) direction of the panel were the same for both FEA tools. The FEMAP value was 0.941 mm (Figure 4) and for LS-DYNA 0.9405 mm (Figure 5). Results in the figures are also expressed in meters. The shrinkage in shorter panel direction for FEMAP and LS-DYNA was the same, around 0.4704 mm.

The results of structural and thermal calculations in comparison to the reference values are shown in Table 3. Stress is calculated for the first ply (bottom ply) of the laminate stack, laying in the direction of the longer edge of the plate.

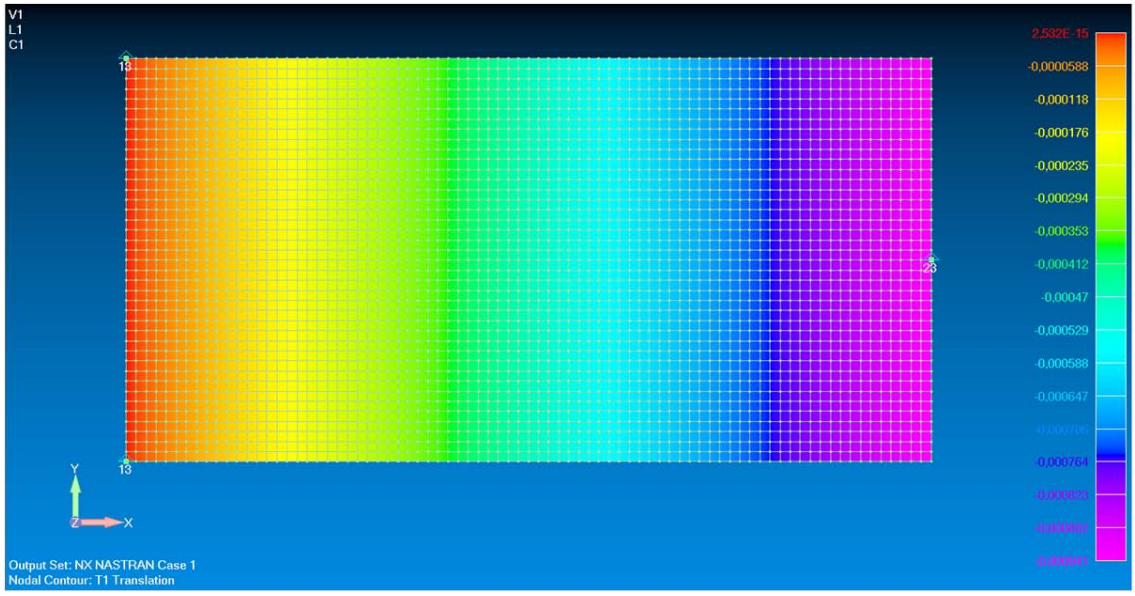

Figure 4 Shrinkage of the composite plate in longer direction of the panel (FEMAP)

Source: Authors

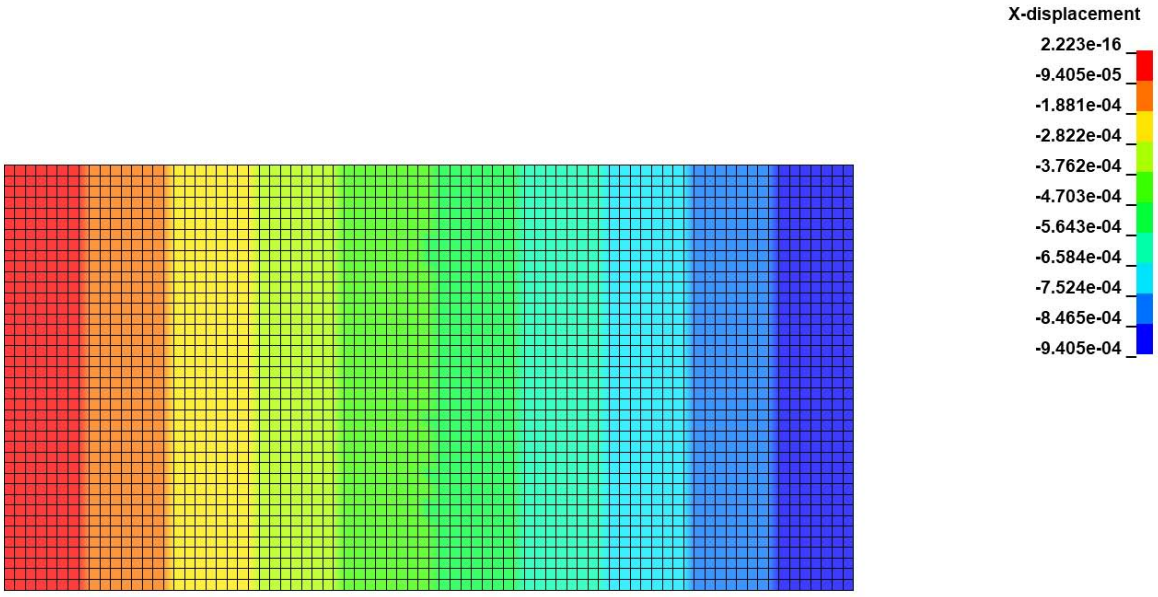

Figure 5 Shrinkage of the composite plate in longer direction of the panel (LS-DYNA)

Source: Authors

Table 3 Comparison table with results for two FEA software

Model type	w_m [mm]	σ_{bm} [MPa]	σ_{am} [MPa]	ΔL_{long} [mm]
Reference values	10.97	18.0	19.4	0.9408
LS-DYNA	8.66	15.2	19.5	0.9405
FEMAP	10.5	14.6	15.1	0.941

Source: Authors

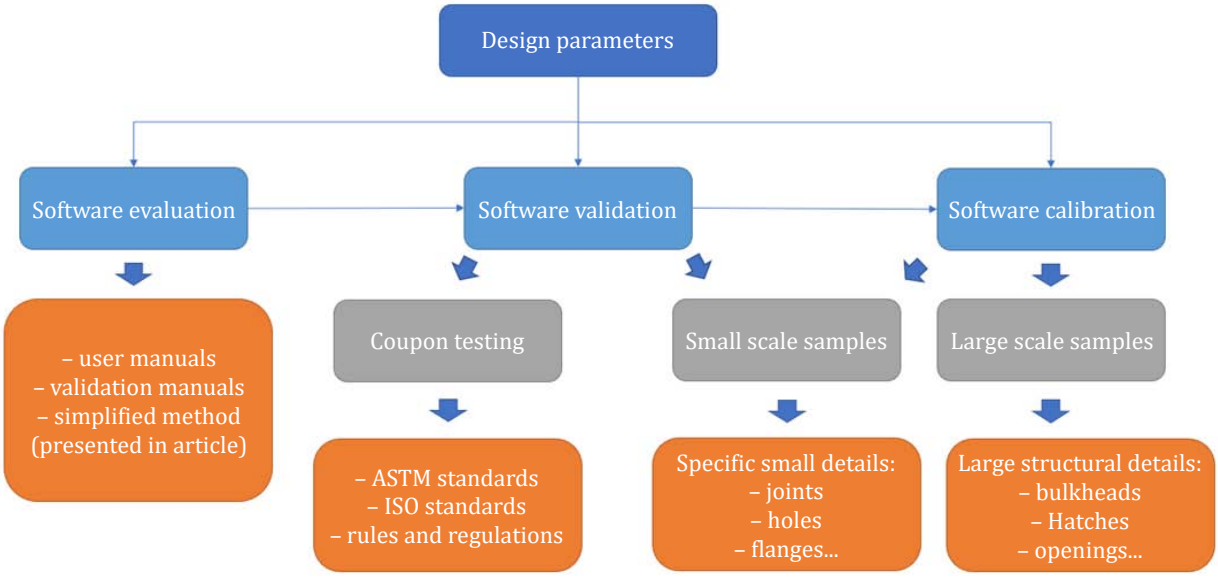

Figure 6 Setting up software design parameters trough evaluation, validation and calibration processes

Source: Authors

4 Discussion of the results

When composite materials are in use, software evaluation, validation and calibration are important steps in the design process (Figure 6). Designers have to rely on the accurate results given by the chosen software platforms, mainly because large scale tests needed to verify the results are usually too expensive to create. The software is usually validated and calibrated using a series of coupon tests (i.e. ASTM E289, ASTM E831 [26]) and small-scale tests in order to compensate for the absence of large-scale testing. The goal of the present research will be to modify the usual design method by simplifying the software evaluation and calibration process, starting with the software evaluation step and reducing the number of required coupon tests.

This article presented the software evaluation part of the design process, where the structural and thermal results can be easily compared. Both FEMAP and LS-DYNA show similar results close to the theoretical values when considering the structural part of the validation process, but there are some discrepancies in final values due to the differences in FEA software solver algorithms used by these software packages as well as the difference in material models used to input the composite laminate properties. Reviewing just the deflection of the plate, LS-DYNA value differs from the reference values for 2.31 mm, while FEMAP value differs from theoretical result for 0.47 mm. Thermal expansion in longitudinal and, especially, in the transversal direction of the plate differs very little from the reference value.

5 Conclusion

The software evaluation samples sometimes can be found as a part of the software documentation, but they are usually calibrated and adjusted to fit the inputs and outputs of particular software. The authors presented material data and reference values for the software validation process which can be used on multiple software platforms. Coupon testing should be reviewed and evaluated in order to reduce the number of tests needed for software validation. Moreover, small-scale problems should be evaluated and synchronized with some of the typical solutions in large-scale testing.

The overall goal will be to give straight guidelines for the composite materials shrinkage design when using composite materials in areas sensitive to temperature changes.

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