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Modelling of delamination in composite shells under different temperature conditions

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Composite shells and panels are widely used in aerospace structures. These are often subjected to defects and damage from both in-service and manufacturing events. Delamination is the most important damage defect. This paper deals with the computational modelling of delamination in laminated composite shells. The use of three-dimensional finite elements for determining delamination of these structures is computationally expensive. Here combined double-layer and single-layer shell elements are employed to study the effect of delamination on the strain values in the sample under purely bending loads. The computational load and the accuracy of the modelling approaches are compared. It is shown that a through-the-thickness delamination can be modeled and analyzed effectively without requiring a great deal of computing time and memory. Some of the results are compared with the experimental results.

Keywords: finite element modelling, delamination, strain, temperature.

1. Introduction

Composites have found extensive applications in several fields such as the aerospace industry, automotive industry, wind energy sector, etc. These composites offer an excellent strength to weight ratio and their use is increasing rapidly. In addition, composites can sustain a range of operating conditions. The manufacturers are producing even larger and critical load-bearing structures. The consequences of failure of such large structures can at best be very costly, and at worst even fatal. To improve the damage tolerance of such structures and, in turn, their safety and reliability an understanding about the behavior of these structure under diverse damage scenarios is required.

It is known that delaminations are the most frequent causes of failure in laminated structures, particularly under compressive load [4]. Delaminations in composite materials result typically from impact damage or manufacturing imperfections. Delaminations in composites plates were studied in detail for flat plates and curved plates in [2, 5, 6, 9, 10]. The modelling approaches have been largely successful for studying the delamination caused during the manufacturing. However, recent studies have shown significance of the effect of ambient temperature on composites, which leads to deterioration of a structure during its exploitation. The modelling of composites under the influence of temperature and its suitability has not been studied yet and as such this is the main contribution of the paper.

In this paper, two modelling strategies were compared for a simple composite beam under bending loads in the presence of different temperature conditions. The developed strategies were compared in terms of computational loads and the agreement with the experimental results under different temperature conditions.

2. Experimental setup

A composite beam (350 × 50 × 3 mm) shown in Fig. 1 was used for the validation of our methodology. Due to the limitations of experimental apparatus, the tests were limited to static loading only. Two loading conditions were used: 100 g (0.98 N) and 200 g (1.96 N).

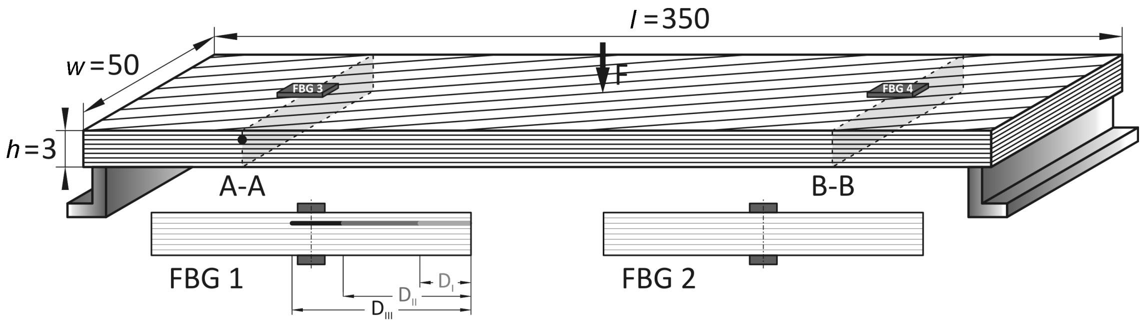

Fig. 1. Details of composite specimen.

The composite beam was made of eight layers of woven fabric of glass fibers (S-glass) with the weave (+45/−45), each layer being 0.2 mm thick. The layers were placed to maintain the symmetry of the composite sample and ensure that the neutral axis (NA) will be at the center. The matrix material was Distitron VE 100. The composite beam was then instrumented with 2 pairs of 1 mm gauge-length FBG sensors.

For the undamaged sample (Damage scenario D_0), the strains were measured for two loading conditions. Once the baseline was established, damage was introduced in to the sample in the form of delamination by inserting a scalpel at the location shown in Fig. 1. The damage extent was increased progressively in three steps (Damage scenarios: D_{I}, D_{II}, D_{III}) as shown in Fig. 2.

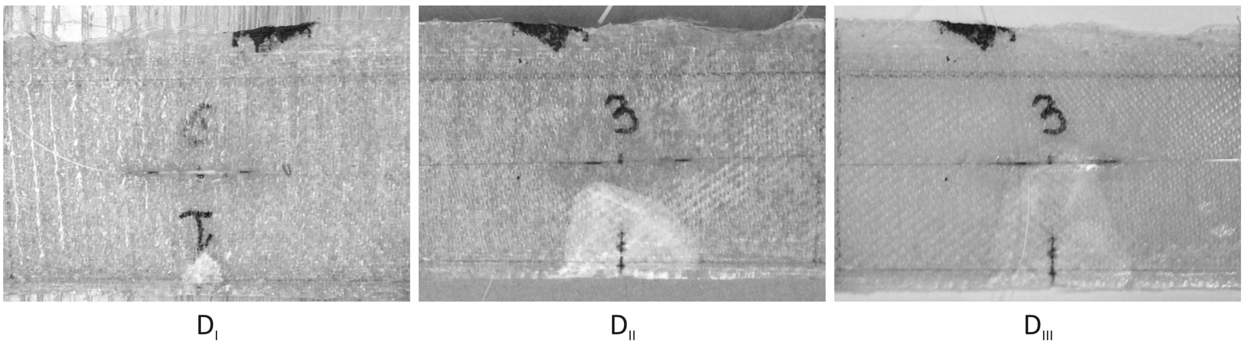

Fig. 2. Three delamination stages [3].

The strain measurements are sensitive to temperature, so in order to minimize the temperature effect, the beam was placed in a heating chamber. The equipment setup is shown in Fig. 3.

The variation of the chamber temperature was ± 2°C and as a result stability of the measurements was still a problem. To minimize the effect of this uncertainty large weights (100 g and 200 g) were applied to the beam, which resulted in large deflection of the beam. The strain measurements were made using the Micron Optics si425-500 interrogator with a sampling frequency of 250 Hz. A temperature sensor was also used along with four strain sensors and it was multiplexed with the sensors to ensure simultaneous strain and temperature measurements.

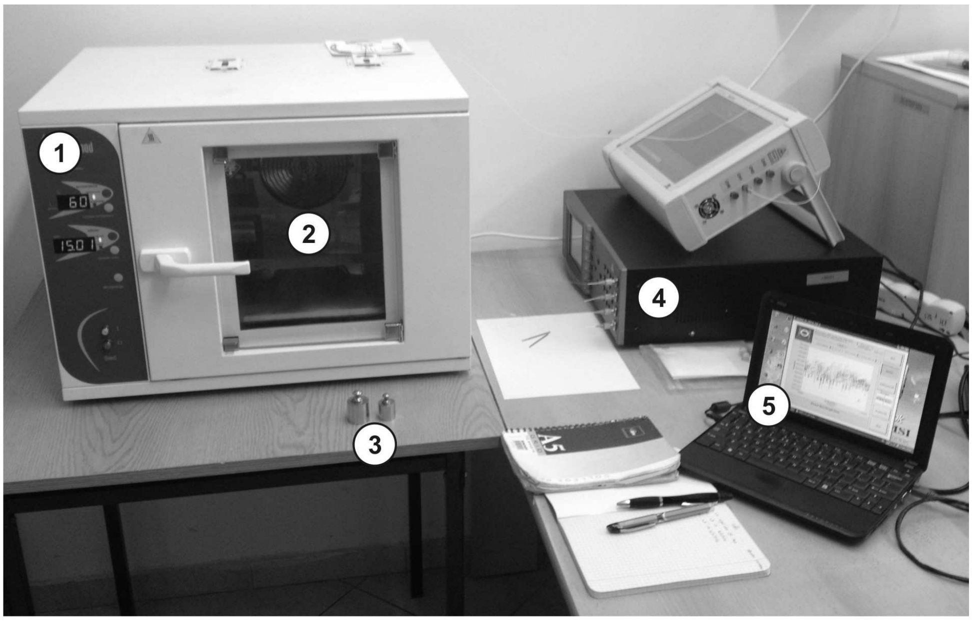

Fig. 3. Experimental setup: heating chamber (1), beam (inside the chamber) (2), weights (3), interrogator (4), laptop (5).

2.1. Strain measurements

Figure 4 shows the strain measured at 20°C for 100 g and 200 g static loading.

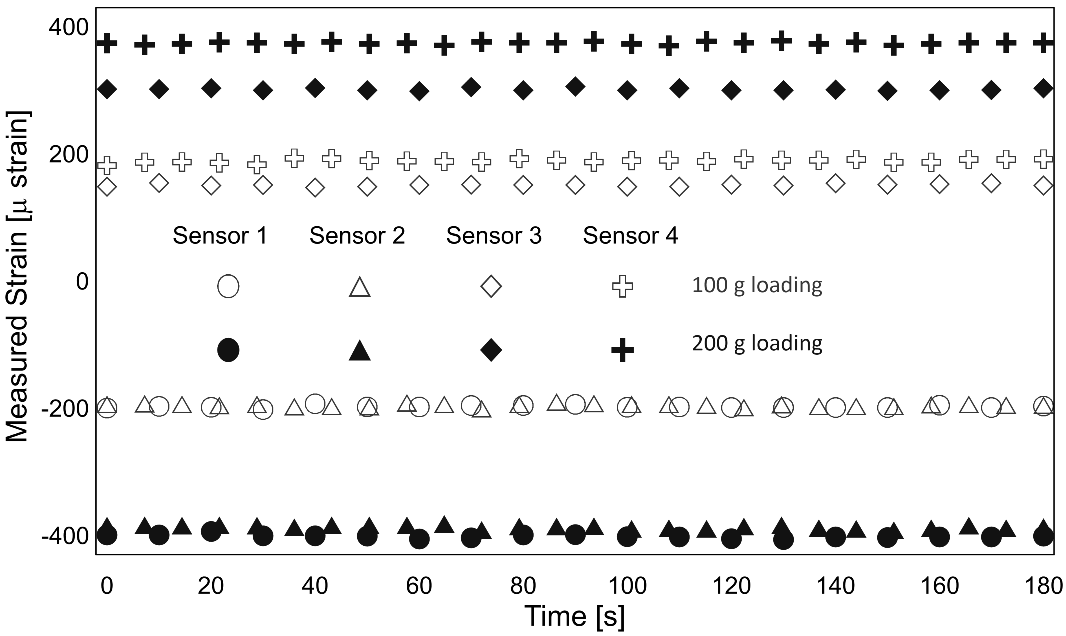

Fig. 4. Measured strain under different loading conditions.

The measured strain for sensors 2 and 4 was equal in magnitude (within reasonable measurement error) but opposite in sign, which was expected. However, the some was not observed for sensors 1 and 3. This unexpected measurement was observed even after the sensor at location 3 was replaced multiple times. Thus, it was concluded that the strain response is lower due to improper manufacturing of the sample. The sample can have excess resin in the region of sensor 3, which results in lower localized flexural rigidity. Inspite of the improper sample preparation, the sensor response remained linear, and the measured strain increased linearly with the load on the structure as well as in the presence of temperature change.

3. Numerical modelling and validation

The simple composite beam was modeled using ABAQUS [1]. The laminates were modeled as node shell elements (S4RT) with six geometric degrees of freedom (dof) per node, and a dof for temperature. The equivalent material properties were assigned using a law of mixtures. The volume fraction was taken as 18%. The value of volume fraction was based on the model updating carried out using the strain values obtained for the static loading scenarios. The boundary conditions were taken as simply supported and the measured strain was compared with the experimental results.

From the experimental data (Fig. 4), it was observed that sensor 3 gives improper strain response, in order to simulate this, the material properties of the model in its region were changed locally. The material properties of the membrane were adjusted to get strain values similar to those for the static loading conditions at 20°C. Two different modelling strategies were undertaken: the double-layer approach and the single-layer approach, which are explained in detail further in this paper. The study was conducted for static loading scenarios and under different temperature conditions. To simulate the bulk temperature effects, different temperature conditions were simulated by specifying the initial temperature conditions and a coupled temperature displacement analysis was carried out.

3.1. Double-layer approach

The beam sample was modeled as two individual laminates assembled together as shown in Fig. 5.

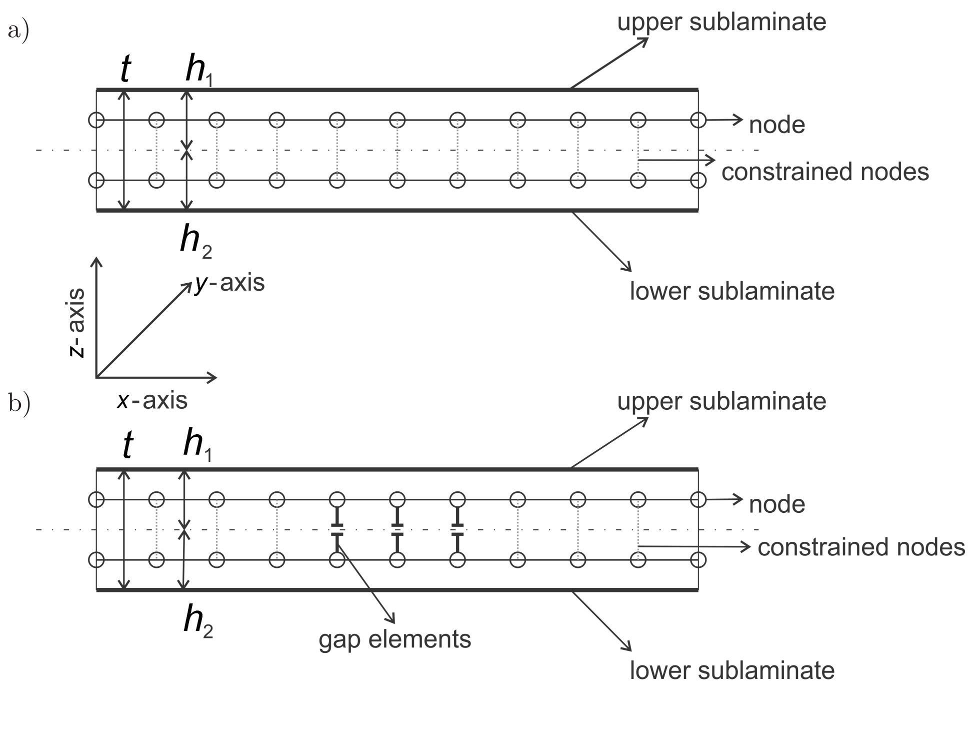

Fig. 5. Modelling strategy for: a) intact sample, b) delaminated sample [8].

The two sublaminates were constrained with the Eqs. (1)–(3) [9]

$$u_x^1 - \frac{h_1}{2}\psi_x^1 = u_x^2 + \frac{h_2}{2}\psi_x^1, \tag{1}$$

$$u_y^1 - \frac{h_1}{2}\psi_y^1 = u_y^2 + \frac{h_2}{2}\psi_y^1, \tag{2}$$

$$u_z^1 = u_z^2, \tag{3}$$

where h_1 and h_2 are the heights of the sublaminates, t is the total thickness of the sample, and superscripts 1 and 2 refer to the upper and lower sublaminate respectively, u_x, u_y, u_z correspond to the displacement along the axes x, y, and z respectively, and ψ_x, ψ_y corresponds to rotation dof about the axes x and y, respectively.

Delamination was modeled by using the gap elements in ABAQUS. The gap elements are ideally suited for the simulations as they allow node to node mechanical contact as well as thermal interactions between the nodes. The regions apart from the delamination were assigned constraint given by Eqs. (1)–(3).

The gap elements were introduced in stages to the different partitions of the model as indicated in Fig. 6. The separation between the gap elements was used as an updating parameter to obtain agreement between the strain values measured and those obtained from the FE analysis.

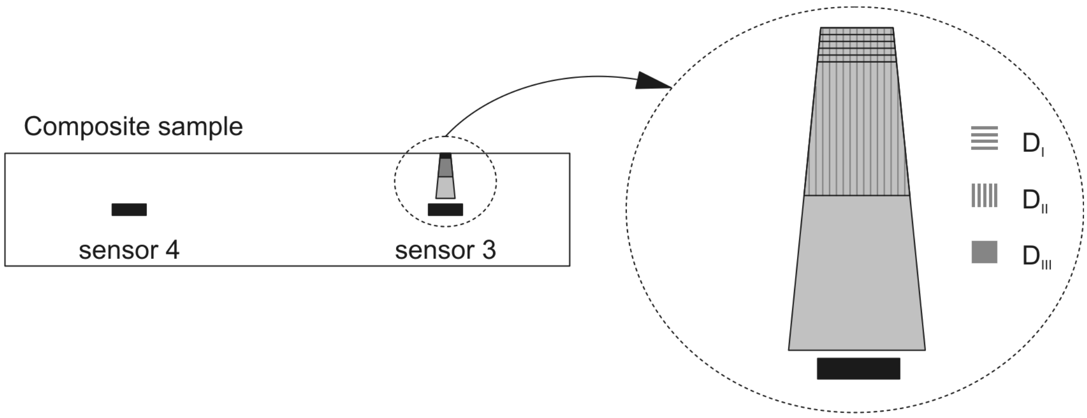

Fig. 6. Schematic indicating delaminated zones in FE model.

3.2. Single-layer approach

In this approach, the intact regions were represented by a single layer of shell elements, whereas the delaminated regions were modeled by upper and lower sublaminates that are connected by contact elements, designated as GAP in ABAQUS as shown in Fig. 7.

For the interface region, a modified version of the sublaminate connection method based on the Eqs. (1)–(3) was used. In addition to the translations, the rotations of all the nodes of the stacked layers at the transition border were coupled as well. Thus, the coupling between the mid-surfaces of the sublaminates of the damaged structure and the mid-surface of the laminate of the intact structure are given by [9]:

$$u_x^1 - \frac{h_1}{2}\psi_x^1 = u_x^2 + \frac{h_2}{2}\psi_x^1 = u_x^0, \tag{4}$$

$$u_y^1 - \frac{h_1}{2}\psi_y^1 = u_y^2 + \frac{h_2}{2}\psi_y^1 = u_y^0, \tag{5}$$

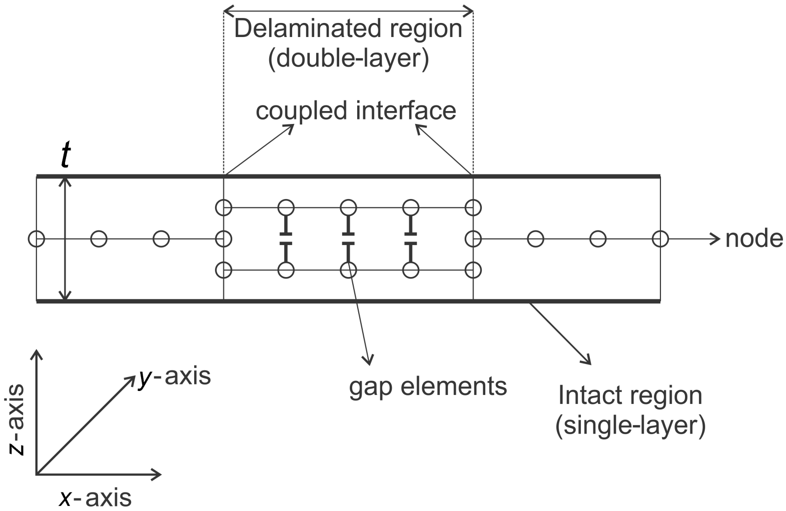

Fig. 7. Modelling strategy for delaminated sample with single layer for intact structure.

$$u_z^1 = u_z^2 = u_z^0, \tag{6}$$

$$\psi_x^1 = \psi_x^2 = \psi_x^0, \tag{7}$$

$$\psi_y^1 = \psi_y^2 = \psi_y^0, \tag{8}$$

$$\psi_z^1 = \psi_z^2 = \psi_z^0, \tag{9}$$

where h_1 and h_2 are the heights of the sublaminates, superscripts 1 and 2 refer to the upper and lower sublaminate respectively, 0 refers to the single laminate for the intact region, u_x, u_y, u_z correspond to the displacement along the axes x, y, and z respectively, and ψ_x, ψ_y, ψ_z correspond to rotation dof about the axes x, y and z, respectively. The delaminated zone again was modeled using gap elements.

4. Comparative study

The two modelling approaches were compared with values from the experimental results. Two different analyses were carried out: static analysis for the "healthy" scenario and each of the three damage scenarios and analysis under different temperature conditions.

4.1. Static loading

The strain values for both modelling strategies were compared with experimental results at four sensor locations and they are shown in Fig. 8. As can be seen for both the modelling approaches, the values are close to the mean obtained from the experiments. Also the accuracy of the value is comparable.

4.2. Temperature loading

For different temperature conditions, the two modelling techniques give comparable results and these results are in good agreement with the experimental results as shown in Fig. 9. Hence, both the modelling techniques can be said to be equivalent.

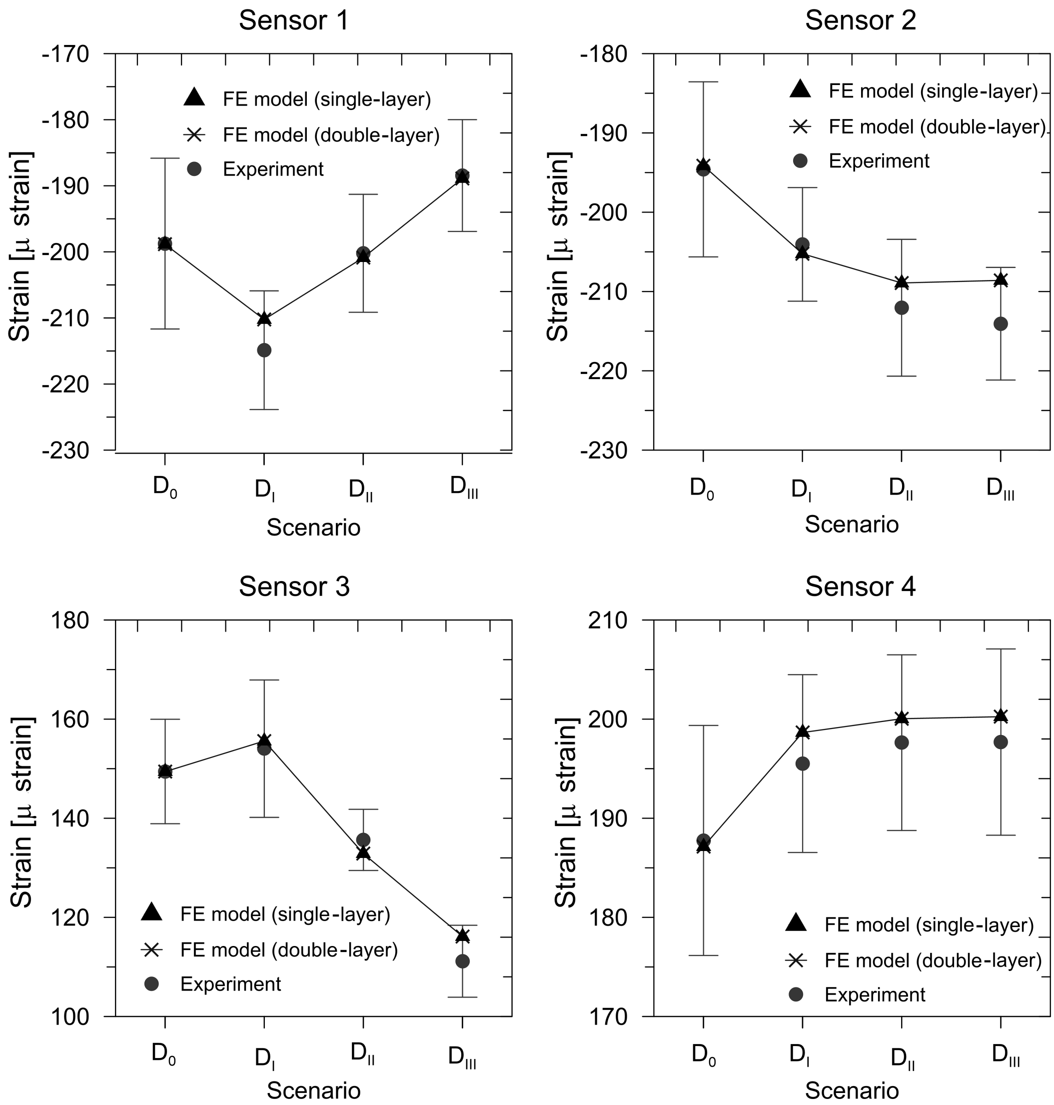

Fig. 8. Modelling strategy for delaminated sample with single layer for intact structure.

The primary difference in the two approaches arises when the gradient temperature effects similar to the one reported in [7] are to be investigated. In [7], the sample is assumed to be experiencing a flux of heat and the temperature variation on the other side of the shell element needs to be calculated. The constraints feature works for the temperature dof as well but a precise estimate of constants is required for realistic estimations, which often need to be assigned based on engineering judgment or estimated based on experimental data that might be hard to obtain. On the other hand, in the single-layer approach the conduction mode is the only transfer of heat available and can be relatively easily modeled. The conduction coefficient and the specific heat capacity need to be obtained experimentally as well.

4.3. Computational effort

As can be seen in the earlier subsections, the performance of the two modelling techniques is comparable. However, the double-layer modelling strategy gives a rise to more elements, nodes and as a result is more computationally demanding. Although the number of nodes and the elements is almost doubled the computational effort is only increased by 20%. This increase in computational

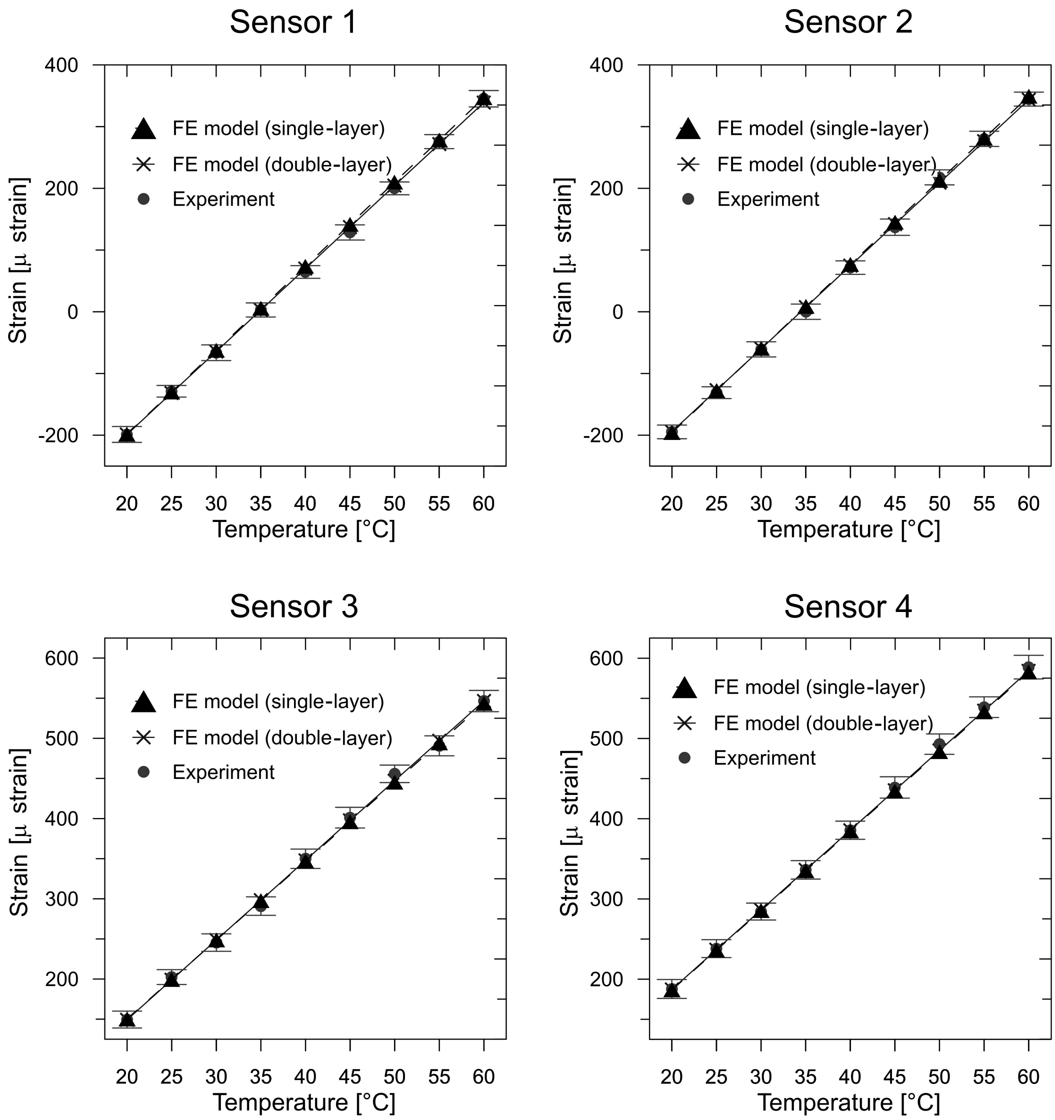

Fig. 9. Modelling strategy for delaminated sample with single layer for intact structure.

load does not significantly improve the computational accuracy. Table 1 presents the comparison between the two approaches.

Table 1. Comparative assessment of modelling techniques.

No.	Parameter	Single-layer	Double-layer
1	Nodes	9624	17 220
2	Elements	9208	16 497
3	CPU time (static analysis)	6.2 s	7.5 s
4	CPU time (temperature analysis)	16.5 s	20 s

It is worth mentioning that for the simple beam structure the computational time required for assessment is limited, but for larger structures with several million nodes and elements the computational time increases several folds and as such is a factor that needs to be given close consideration.

5. Conclusions

The paper presented two different strategies for modelling delaminations in the composite. The modelling results are compared with experimental data under static loading and under different temperature conditions. This study also compared the computational effort needed for the two modelling approaches. It also provided the theoretical background for maintaining the physical and mechanical aspects of the modeled beam. Based on the results shown, it is evident the two approaches are not significantly different with regard the strain values obtained. In addition, the computational efforts required are increased approximately by 20%, but for the given application this increase is not significant.

For the gradient temperature effects it might be easier to model the sample as a single-layer approach as the double-layer approach requires additional assumptions or simplifications in comparison to the single-layer approach (radiation, convection contributions). Despite the above, the double-layer approach gives more flexibility for incorporating more delamination zones in the sample or for modelling progressive damage scenarios in which the delamination zone is increasing in length. Therefore, based on application an appropriate modelling strategy can be chosen.

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