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Sensitivity analysis for simulated testing of composites: mapping via Isight and Abaqus

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Summary. This article reports the effects of multiple interactive material parameters of composite material on the deformation response during a simulated three-point bending and tensile testing. The test specimens for both scenarios were modelled for a finite element analysis, where the laminated material was described using nine material parameters. Isight® and Abaqus® codes were used to map interactive combinations of material parameters to study the specimen-level effects of simulated aging. The procedure was defined using Latin Hypercube Sampling. Based on our analysis, a specific combination of parameters can be traced to cause the stiffness degradation due to simulated aging. These results are highly beneficial when developing numerical methods to analyse aging behaviour of composite structures.

Key words: composite, aging, Abaqus, Isight

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Introduction

Composite materials can be used in highly requiring applications, such as reactor tanks for the process industry [1] due to the inherent resistance against chemicals. However, during a prolonged operational lifetime, the harsh environment will cause aging. It will have an effect on the composite material used. The resulting material property deterioration in the micro and macro scale is not evident [2, 3].

In the long run, any environment degrades the material properties of polymeric systems. Especially fibrous composite materials are challenging to analyse considering the aging response. Composites are not isotropic and the describing of the material over the Hooke's law regime requires nine parameters, which are Young's moduli, shear moduli and Poisson's ratios in all the three directions. Moreover, these parameters do not have a straightforward relation similarly as for isotropic materials. The question from the numerical analysis point of view is how to define relevant parameters when modelling the environmental effects of laminate or an entire structure.

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Studies of laminate aging have mainly been experimental [4, 5]. Experiments have concentrated on defining aging influence on stiffness and strength. An interest has been in understanding ageing mechanisms, such as chemical and physical changes [6]. The developed aging models concentrates on modelling how the specific property changes during time. The statistical methods combining several material parameters are limited for studying material property deviation effect on the laminate response [7, 8].

In this work, our target is to study ply-level material properties and their interactive effects on the specimen-level deformation. The study is performed using two different simulation scenarios, which are the three-point bending and tensile testing. Proper test specimens were modelled for a finite element (FE) analysis. We used a sampling method for studying different combinations of parameters values to understand the influence on the deformation response. We applied the Isight® tool, provided by Simulia, to automate the sampling, FE analysis and post-processing.

Materials and methods

Materials

The modelled materials corresponded a composite system reported previously [3]. The reinforcing glass-fibre was E6CR17-2400-386 (Jushi) and resin Derakane 441-400 (Ashland). The ply properties were not known beforehand and initial values were estimated using the rules-of-mixture with a fibre volume content of 51%. For micromechanical models, the Young's modulus of the glass-fibre and resin were set based on the manufacturers' technical data sheets: glass-fibre and resin Young's moduli were 79.79 GPa and 3.3 GPa, respectively [9, 10]. Poisson's ratios were approximated based on values reported in the current literature: the applied Poisson's ratios were 0.2 and 0.38 for glass-fibre and resin, respectively [11]. The final ply properties are described in Table 1.

The test specimens virtually prepared of the composite material corresponded to the standard specimen configuration per test standard: ASTM D2344 and ISO 527-5 for interlaminar shear strength (ILSS) testing (i.e. three-point bending) and tensile testing, respectively. Both tensile test and three-point bending specimens were modelled using the ply material model of the glass fibre/vinyl epoxy resin composite.

The tensile test specimen had tabs, which were made of glass fibre fabrics and epoxy. The tab material properties were approximated based on typical material properties provided by the ESAComp software [12]. The applied material properties are shown in Table 1. The three-point bending scenario included three loading pins, which were modelled as structural steel (Young's modulus 210 GPa, Poisson's ratio 0.33).

Finite element models

The FE models (Figure 1), representing the three-point bending and tensile test specimens, were created using Abaqus 6.14 (Simulia). Both specimens were modelled using the similar laminate (and ply model). The laminate consisted of 11 plies, two 560 g/m^2 plies (90˚ orientation against specimen longitudinal axis) of and nine 450 g/m^2 plies (0˚ orientation). The stacking sequence of the laminate was $[0_4/90/0/90/0_4]$ and the

Table 1. Composite material properties applied for FE models in this study.

Property	Ply (unaged)	Tab laminate
E_1 [GPa]	42.36	24
E_2 [GPa]	6.64	24
E_3 [GPa]	6.64	9
G_{12} [GPa]	2.42	3.6
G_{13}, G_{23} [GPa]	2.42	3.5
$\nu_{12}, \nu_{13}, \nu_{23}$	0.288	0.3

laminate thickness was 4 mm. Layer thicknesses were assumed to be proportional to the areal masses.

The three-point bending specimen's width was 10 mm and length was 26 mm. The three-point specimen was supported by two loading pins, which had a diameter of 3.2 mm. The span between the support pins was 18 mm. The loading was subjected via one loading pin (diameter of 6.3 mm) placed in the centre of the support pins' span. A contact was modelled between the pins and the specimen. All the cylindrical pins were modelled as a half cylinder, where boundary conditions were attached to the straight (level) surface. All displacements were restricted for the lower support pins. For the loading pin, horizontal displacement was restricted. The load was performed using enforced displacement perpendicular to the specimen ply plane.

The tensile test specimen had length of 250 mm and its width was 19.86 mm. The loading tabs were placed in both ends of the specimen. The length of a tab was 50 mm and thickness 2.5 mm. The tab was also a laminate for which the material coordinate axis was set at a 45° angle to the longitudinal axis of the laminate plane. The tabs were attached to the specimen using a tie constraint. The loading was applied on the surfaces of the tabs. The end tab displacements were restricted in the width and thickness direction. Enforced displacement was defined for the other end tab parallel to the specimen longitudinal axis.

Isight

Isight is a process integration and design optimization tool provided by Simulia. Isight automates an analysis where several alternative design parameters can be used. Isight can be linked with several other analysis applications, e.g., Abaqus, Matlab and Excel.

The input parameters for Abaqus model were ply properties, which were numerically altered in Isight to simulate virtual aging in our analysis. As a process step, Isight provided the mapped material parameters as an input for Abaqus, which performed the defined load step of the FE simulation (enforced displacement). The Abaqus results were imported back to Isight, where post-processing of the results were performed. The Isight design workflow of this study is shown in Figure 1.

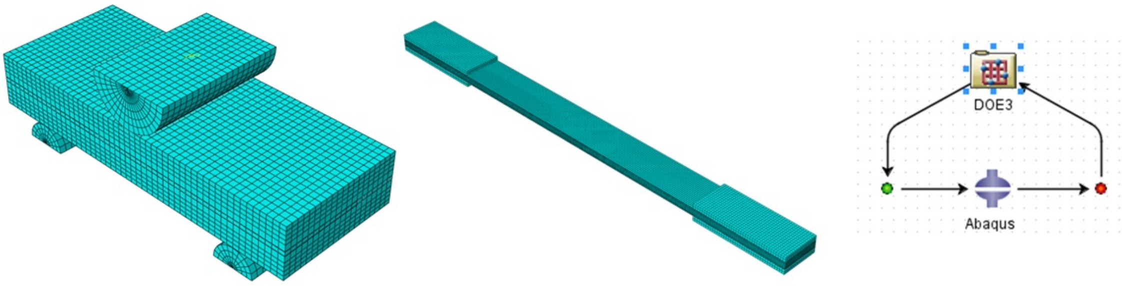

Figure 1. The finite element models of a three-point bending (left) and tensile specimen (middle). The applied Isight design workflow describing the process steps (right).

We used optimal Latin Hypercube Sampling method (LHS) for defining the material property combinations for the mapping. In a traditional LHS method, each parameter is divided into equal spaced intervals; a user defines the number of intervals and the minimum and maximum value for each parameter. The minimum value was half of the maximum value. In LHS, a parameter value is chosen from each interval. In optimal LHS sampling, the combinations are optimized to cover each parameter range evenly. A sample of applied combinations used in three-point bending are shown in Appendix A.

The parameter sensitivity on the target response was studied using a regression analysis. The regression analysis results were determined using linear term correlation factor (LCF) per each material parameter. The factors presenting interaction between parameters were not individually covered. The target response was the stiffness (deformation) of the simulated test specimens in the direction of the enforced displacement (load).

Results

Three-point bending

The results of the three-point bending analysis are shown in Figure 2 (left). We used two analysis sets, which had 50 and 200 sampling points and the linear correlations had a very small variation between these analysis sets. The longitudinal Young's modulus clearly highlights its remarked influence on the response. Three other parameters are seen rather critical as well: the out-of-plane Young's modulus (E_3) and shear moduli referring to the out-of-plane direction, G_{13} and G_{23}. This effect by the shear moduli is assumed to be due to the 90˚ plies. The effect of the Poisson's ratios on the results is relatively low, such as the effect by the shear modulus G_{12} and Young's modulus E_2. In fact, the E_2 parameter has a negative coefficient, which indicates decrease in the target response when increasing the value.

Tensile testing

The results of the tensile testing analysis are shown in Figure 2 (right). Again, we used two analysis sets, which had 50 and 200 sampling points. The number of points in the analysis set does not indicate any difference when E_1 is of concern. A difference is observed when comparing factors of other parameters. However, the difference is minor in general and negligible in relation to sensitivity of the response to E_1. The fibre direction Young's modulus (E_1) is the main explanatory variable for the tensile deformation, and the property has a linear correlation factor with almost full (unit) value. For the other parameters the contribution to tensile stiffness is negligible. There was a slight sensitivity to the parameter values of E_2, E_3 and G_{13}. The transverse Young's modulus (E_2) is rather irrelevant, naturally, when only two 90˚ plies are present in the lay-up [2].

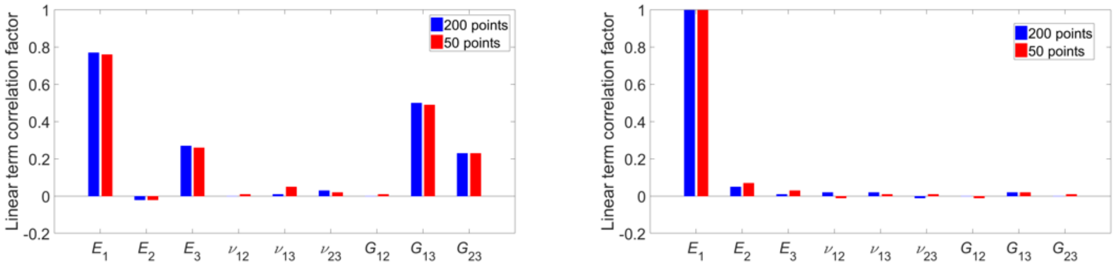

Figure 2. Result of three-point bending (left) and tensile testing (right). The vertical axis indicates the linear term correlation factor (LCF).

Conclusion

We used an automated computational routine involving Isight and Abaqus process steps for studying the degradation of material properties and the related sensitivity during simulated tensile testing and three-point bending testing. We applied valid lay-up and material properties for the fibre and resin of the composite material system on the micro-length scale according to the current literature. Our sensitivity analysis on the ply-level remarked a major effect by degradation in (fibre) longitudinal direction parameters for both modelled specimen types. For the three-point bending specimen, E_3, G_{13} and G_{23} also indicated a clear influence on the simulated stiffness and given degradation range. We conclude that to understand the causes of aging in the modelled laminate, the focus should be directed on the highly matrix-dependent properties when stiffness deterioration is observed during three-point bending while during tensile testing deterioration can only result due to fibre damage.

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Appendix 1. A sample of data matrix (three-point bending, 200 points).

	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	ν_{12}	ν_{13}	ν_{23}	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]
1	24.91	5.58	6.61	0.247	0.147	0.241	1.70	1.64	1.55
2	22.35	5.56	4.54	0.185	0.278	0.244	1.64	2.21	2.21
3	21.39	4.81	5.31	0.266	0.273	0.219	2.03	2.29	1.62
4	25.44	6.31	3.89	0.228	0.283	0.234	1.41	1.51	1.61
5	35.76	5.46	3.96	0.146	0.148	0.216	1.34	1.76	1.81
6	36.83	5.89	6.44	0.179	0.243	0.201	2.31	1.47	1.49
7	33.21	4.26	3.79	0.177	0.154	0.266	2.06	1.44	2.04
8	26.61	5.02	5.88	0.145	0.172	0.236	1.75	1.23	1.69
9	22.24	4.76	3.76	0.171	0.213	0.178	1.24	1.96	1.84
10	37.78	3.81	6.34	0.179	0.190	0.232	1.73	2.15	1.21
11	32.46	4.96	4.94	0.166	0.197	0.149	1.30	1.50	2.31
12	29.27	5.93	6.23	0.230	0.216	0.169	2.08	2.31	1.27
13	28.52	5.59	3.47	0.259	0.179	0.281	2.17	2.18	1.93
14	23.73	6.49	5.04	0.176	0.178	0.202	1.42	1.84	1.35
15	30.76	4.86	4.44	0.216	0.237	0.156	1.47	2.42	2.35
16	22.67	4.64	5.93	0.182	0.219	0.279	2.00	1.73	2.31
17	21.61	5.53	5.44	0.191	0.161	0.169	1.74	2.13	2.22
18	28.84	6.04	6.06	0.161	0.176	0.198	2.32	1.55	2.26
19	39.81	5.73	5.91	0.276	0.192	0.268	1.87	1.72	2.29
20	30.97	5.09	5.31	0.152	0.284	0.282	1.93	1.63	1.59
21	24.05	5.64	5.84	0.204	0.174	0.153	2.18	1.48	1.42
22	28.10	4.29	6.11	0.279	0.229	0.154	1.86	1.42	1.44
23	40.02	6.16	6.13	0.219	0.148	0.243	2.07	1.81	1.42
24	35.87	6.46	4.81	0.186	0.228	0.277	2.21	1.53	2.24
25	28.31	5.91	3.41	0.245	0.271	0.211	2.33	1.70	2.11