CHAPTER - 8

VALIDATION OF TEST RESULTS USING FEA

The tensile and flexural test specimens of Fibre Metal Laminate (FML) composite are modelled using MIDAS NFX Finite Element Analysis (FEA) Software [1] to verify the deformation and tested failure strength. This chapter explains the process of finite element modelling and the correlation of the FEA results with the experimental test results.

8.1. MIDAS NFX FEA SOFTWARE

MIDAS NFX is an integrated design and FEA software from MIDAS IT Korea [1]. MIDAS suite of mechanical and civil analysis software is used by 30000+ users in over 120 countries. MIDAS NFX offers seamless 2D and 3D Finite Element (FE) modelling of complex mechanical systems. It has parallel processing capabilities to optimise and perform multi-physics analysis including fluid structure interaction and non-linear analysis. The accuracy of MIDAS NFX FEA software has been validated and verified through a number of benchmarks as recommended by The International Association for the Engineering Modelling, Analysis & Simulation Community – NAFEMS. One of the advantages of MIDAS NFX FEA software is that the developed models can also be easily exported to widely popular MSC NASTRAN solver. MIDAS NFX is affordable and fast FEA solver and hence was selected for modelling of the FML composite and simulation of the tensile and flexural tests.

8.2. MECHANICAL PROPERTIES & MATERIAL MODELLING

The constituent materials of the FML composites are Woven E-Glass, Uni-directional (UD) High Strength (HS) Carbon, Aluminium Alloy 1100 and Epoxy resin. The isotropic properties of cured neat Epoxy LY556 resin mixed with HY951 hardener in the ratio of 10:1 are taken from Refs. [2]. The mechanical properties of the 0/90 woven E-Glass fabric reinforced epoxy (50% fibre volume fraction) and UD Carbon tape reinforced epoxy (60% fibre volume fraction) are taken from Hexcel

Prepreg Technology Handbook [3]. The mechanical properties for the cured composite material impregnated with epoxy resin and Aluminium Alloy 1100 as used for the FEA are given in Table 8.1. The symbols are typical elastic modulus, Poisson ratio and shear modulus. The subscripts 1 and 2 refer to the property in fibre and material directions of the composite. For isotropic materials, the properties in 1 and 2 directions shall be equal.

Table 8.1: Mechanical properties for FEA

Material	**E_{11} (MPa)**	**E_{22} (MPa)**	**G_{12} (MPa)**	**n_{12}**
E-G/EP (Woven)	20000	19000	4200	0.13
HS-C/EP (UD)	130000	9000	4400	0.25
AL 1100	70000	70000	26316	0.33
Epoxy	3300	3300	1241	0.35

The cured ply thickness of composite layers are influenced by a number of factors such as the application of resin impregnation using rollers during fabrication as well as the placed weight over the fabricated FML composite during room temperature cure. Based on close examination of cut-up micro-section photos of the cured FML composite specimens, it has been established that the bond line thickness between the layers is typically 0.1mm. This quality of bond line is also reported in other researches [3-4]. Based on this and considering 0.3mm Aluminium layer thickness and cured specimen's total thickness of FML01 - {AL/G/G/AL/G/G/AL}, FML02 - {Al/C/C/Al/C/C/Al}, and FML03 - {Al/G/C/Al/C/G/Al} as 3.5mm, 3mm and 3.1mm respectively, the cured ply thicknesses for the composite layers are arrived. The stacking sequence and layer arrangements considered for the FEA of FML01, FML02 and FML03 specimens are shown in Figure 8.1. The subtle difference in the cured ply thickness of UD Carbon ply for FML02 specimen is noted and adjusted to match the cured specimen total thickness of 3mm.

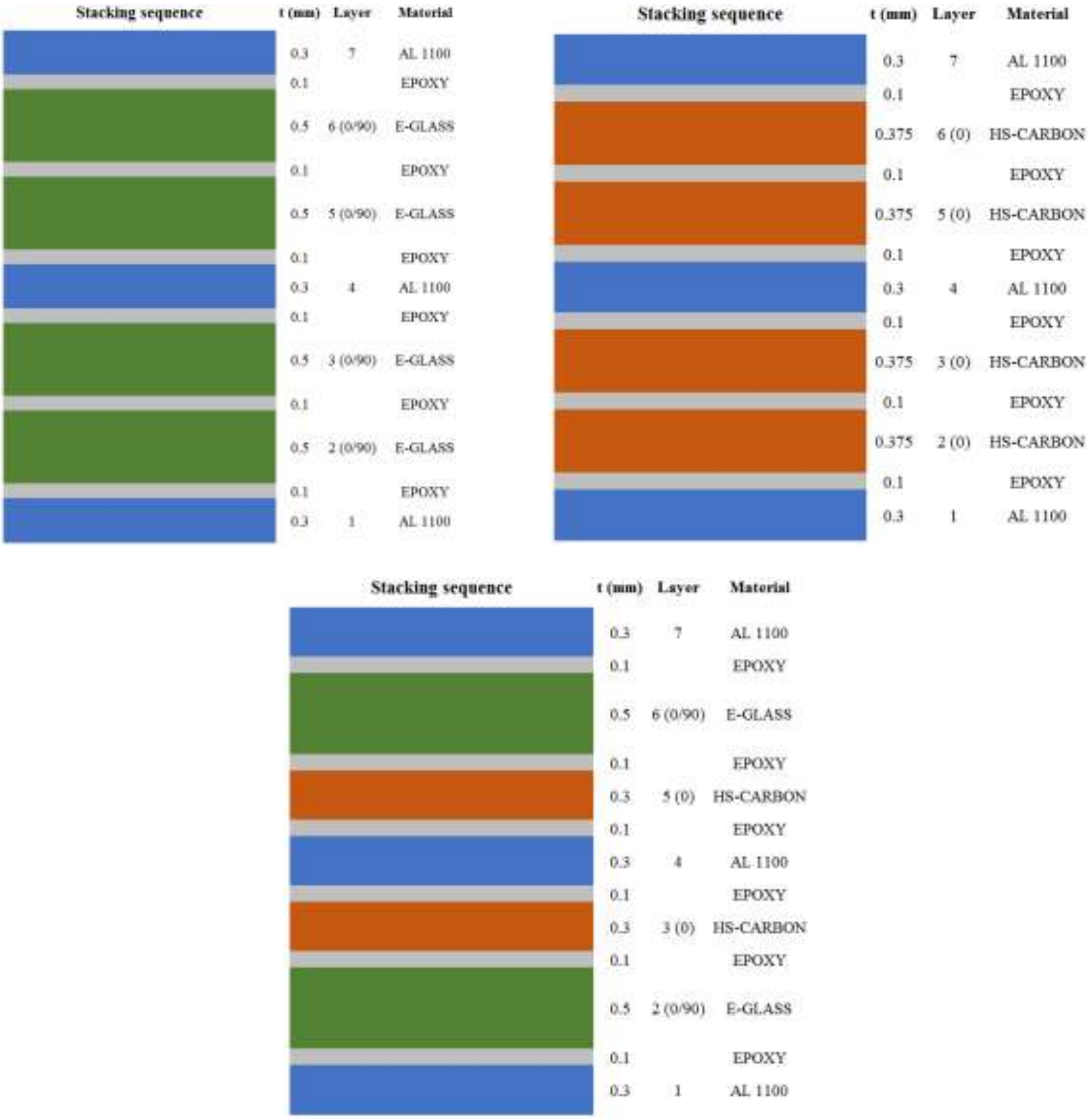

Figure 8.1: Stacking sequence for FEA of FML01 (top left), FML02 (top right) and FM03 (bottom)

The woven E-Glass fabric material with orientation 0°/90° and UD HS-Carbon tape material with orientation 0° are idealised using CQUAD4 type two dimensional (2D) SHELL elements by defining a PCOMP material property card that is available in MIDAS NFX FEA software for defining composite materials. The 0° orientation is aligned to the X-axis of coordinate system being the direction along the specimen length. The Z-axis of the coordinate system is through the thickness starting from layer 1 to 7. The 2D SHELL elements are positioned at the mid-layer thickness. The Aluminium alloy 1100 and Epoxy layers are modelled using CHEXA type three dimensional (3D) BRICK elements. In order to avoid double accounting the extra thickness of resin layer (real thickness being 0.1mm) between the Aluminium and composite layers, the elastic modulus of resin (Err) layer with in the model is corrected with modelled thickness (tm) using Err = Er * 0.1/tm. Er is the elastic modulus of neat epoxy resin. For example, for FML01, the elastic modulus of the 0.6mm thickness epoxy layer for the FEA is 3300*0.1/0.6 = 550 MPa. Figure 8.2 shows the idealisation of FML composite specimens using 2D SHELL (extended lines) and 3D BRICK elements.

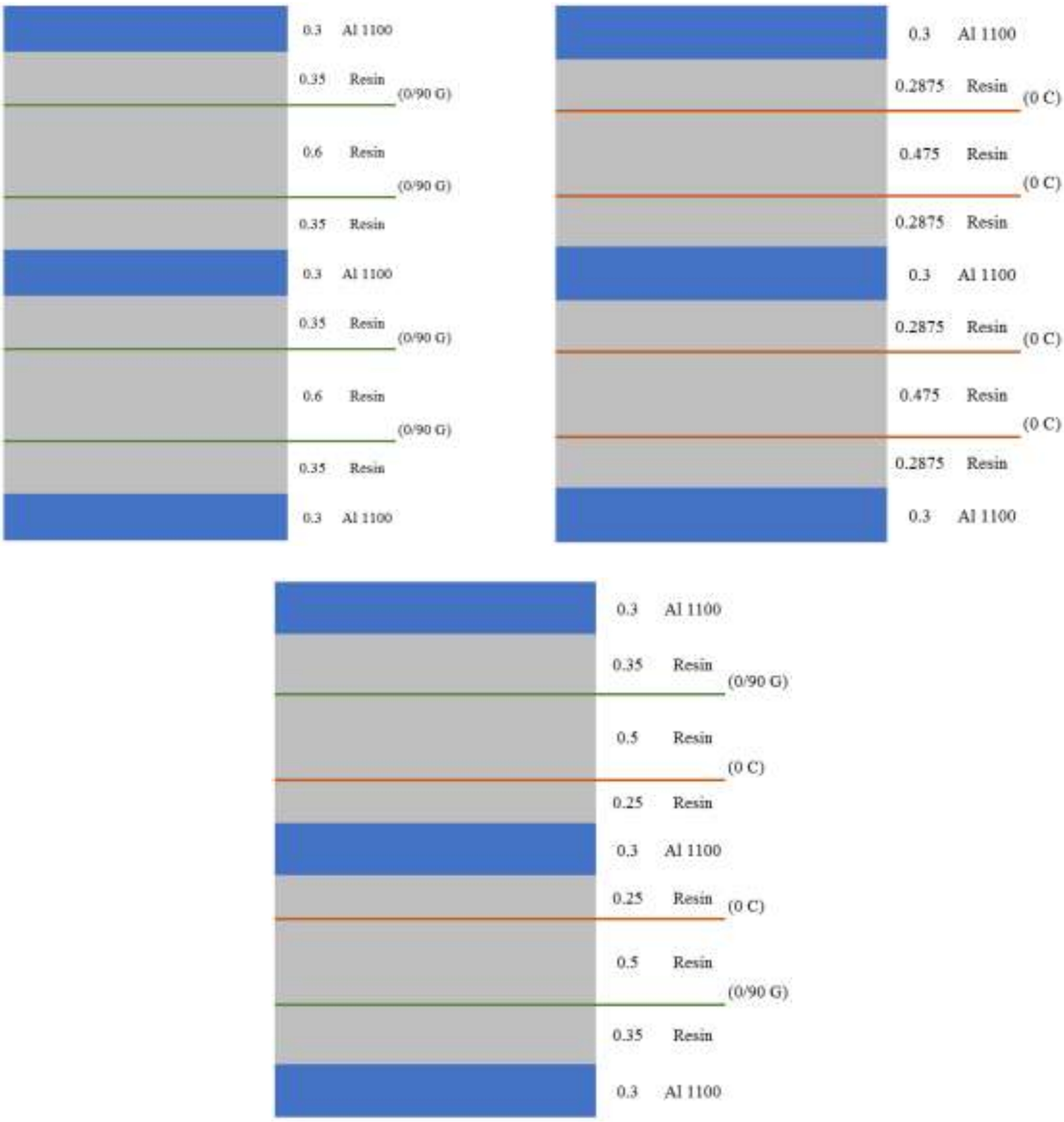

Figure 8.2: Idealisation of composite and metallic plies for FEA of FML01 (top left), FML02 (top right) and FML03 (bottom)

8.3. FINITE ELEMENT MODELLING

The dimensions of FML composite specimens modelled in MIDAS NFX FEA software are shown in Table 8.2. The refinement of finite element mesh is maintained such that the element length along the length and width of specimen as 1mm and 0.8mm respectively. The element length through the thickness has matched the required resin layer thickness as explained earlier. For the thicker resin layers (3^{rd} block of BRICK elements from the top and bottom), half-thickness is used as element length. A further refinement of mesh along the mid-width and mid-span is carried out to accurately extract the layer stresses from the FEA. Figures 8.3 to 8.5 show the robustness of mesh refinement using FML03 tensile test specimen as an example. For all the FEA simulations, the level of mesh refinement is maintained more or less the same. This level of mesh density is deemed accurate [5]. A summary of the number of elements and nodes for each model is listed in Table 8.3.

Table 8.2: Dimensions of FML composite specimens

FML \ Test	Stacking Sequence	Tensile test (mm)	Flexure test (mm)
FML01	{AL/G/G/AL/G/G/AL}	150×30×3.5	120×30×3.5
FML02	{AL/C/C/AL/C/C/AL}	250×25×3.0	120×30×3.0
FML03	{AL/G/C/AL/C/G/AL}	250×25×3.1	120×230×3.1

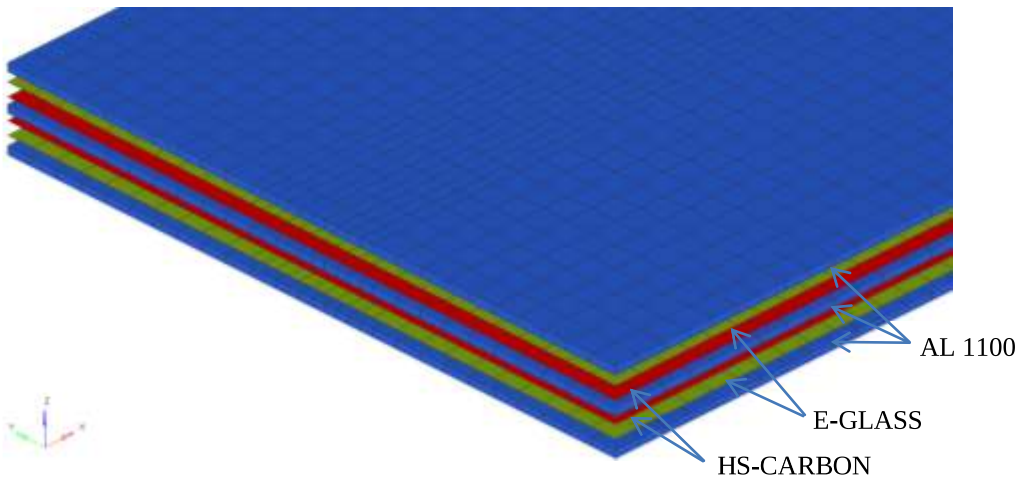

Figure 8.3: FE mesh of FML reinforcement layers (resin mesh not shown)

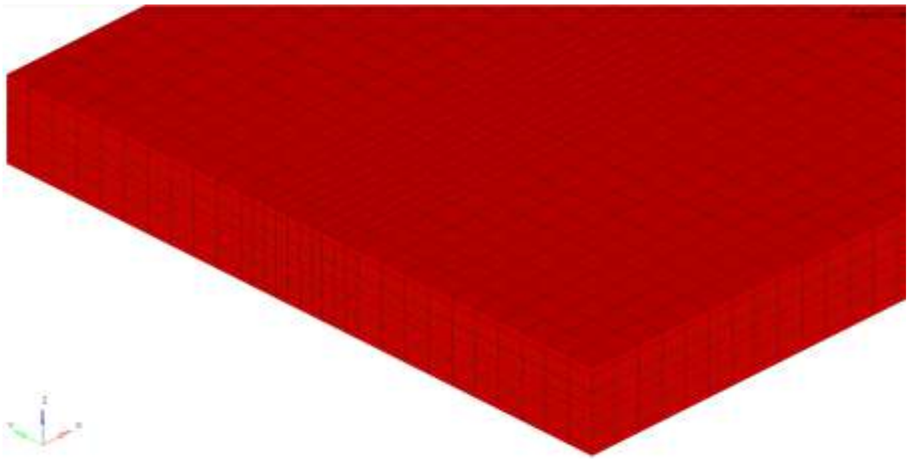

Figure 8.4: FE mesh refinement at edge of the specimen

Figure 8.5: FE mesh refinement at mid-span the specimen

Table 8.3: Dimensions of FML composite specimens

Test	FML	Model #	CHEXA	CQUAD4	Nodes
Tensile	FML01	M111	57596	20944	65100
	FML02	M211	83820	30480	94860
	FML03	M311	83820	30480	94860
Flexure	FML01	M112	57596	20944	65100
	FML02	M212	60016	21824	67500
	FML03	M312	60016	21824	67500

8.4. BOUNDARY CONDITIONS & LOADING FOR FEA

In FEA, the idealisation of real test conditions in most representative yet accurate way becomes an important aspect to rely on the outcome of simulation [6]. Verified boundary conditions (BC) from the research work of Lilly Mercy [5] are used for the FML specimens. The loading and boundary conditions are applied using a combination of nodal constraints and RIGID BODY type element with its MASTER node being dependent on all the degrees of freedom for tensile test and TZ degrees of freedom for flexural test. For tensile test, the master node of left hand side RIGID element is constrained in all degrees of freedom to simulate a clamped boundary condition and uni-axial tensile load in X-direction is applied at the master node of right hand side RIGID element as shown in Figure 8.6 (e.g. FML01). The RIGID BODY element covers the nodes within the clamping tabs for the tensile test machine. This clamp tab lengths at each end for the tensile tests are 30mm and 50mm respectively for the FML01 and FML02/FML03 specimens.

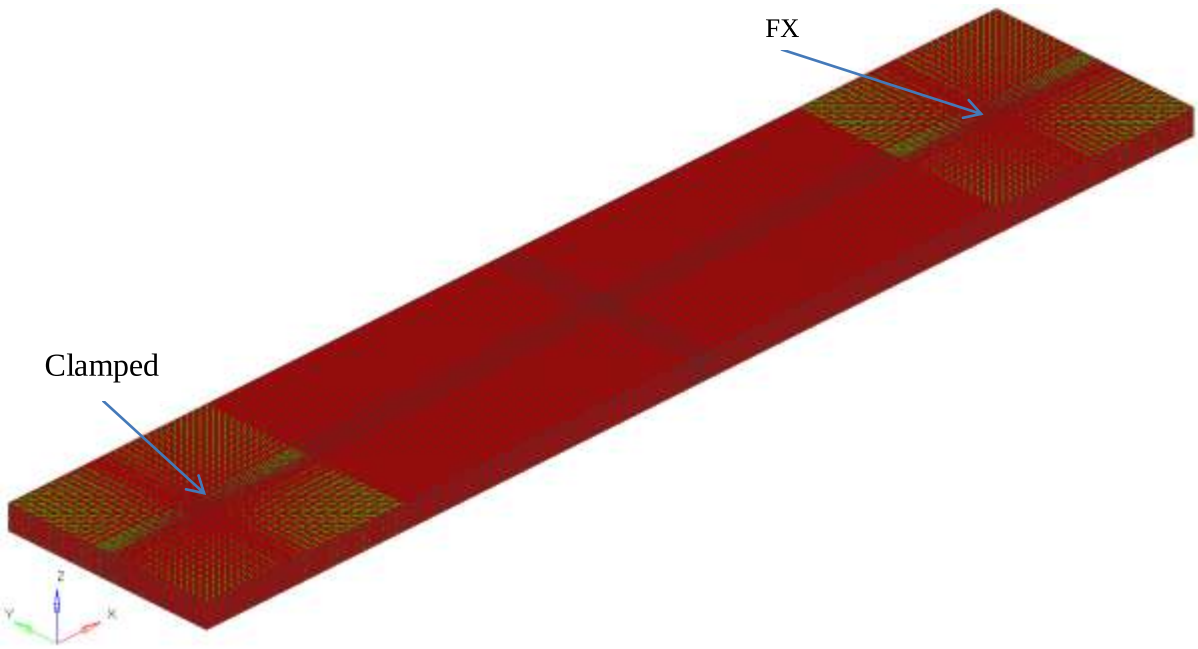

Figure 8.6: Boundary conditions and loading for tensile test (e.g. M111)

For the three point bending (flexure) test specimen FEA, the nodes on the specimen in contact with support rollers are constrained as TZ = 0 to idealise a simply supported boundary condition. For all the flexure test FEA simulations, the distance between the support rollers is maintained as 100mm. The nodes on the specimen in contact with loading roller are constrained as TX = 0 and TY = 0 to idealise no-slip during loading. A vertical load in Z-direction is applied at the master node of loading roller RIGID BODY element as shown in Figure 8.7.

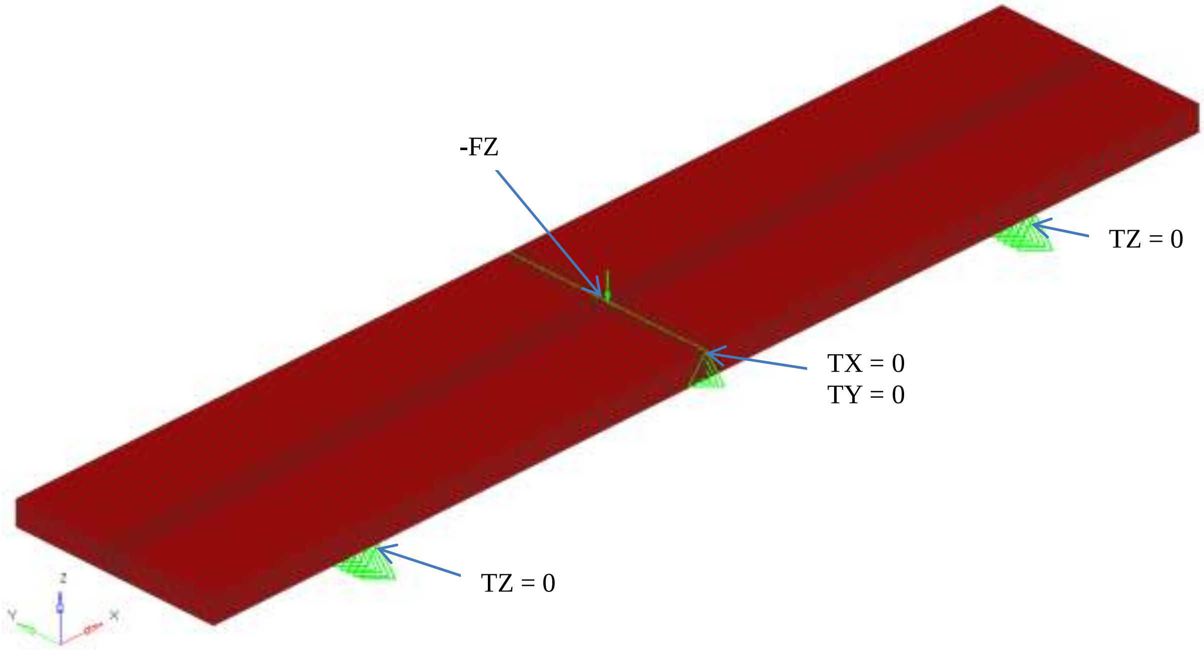

Figure 8.7: Boundary conditions and loading for flexure test (e.g. M112)

8.5. VALIDATION OF BC & MESH DENSITY

For simplicity and validation of FE modelling principles, boundary conditions and loading for tensile and flexure test FEA simulations, the isotropic properties [3-4] of cured neat Epoxy resin, E = 3300 MPa and ν = 0.35 are applied to all the 3D Brick elements after deleting the 2D SHELL elements. The fringe plots of displacement and mid-span stress tensor in the X-direction from the linear static analysis with neat resin properties for FX = 25 kN applied load are presented in Figure 8.8 and Figure 8.9 respectively. The correlation of hand calculations and FEA simulations is given in Table 8.4. The FEA results are within 1% error margin compared to the theory. This validates the BC and mesh density adopted for tensile test FEA.

Table 8.4: Tensile test BC validation using neat resin property, FEA vs. Theory

TENSILE TEST	**FML01**	**FML02**	**FML03**
Material	Epoxy	Epoxy	Epoxy
FEM No.	M101	M201	M301
Length (mm)	150	250	250
Distance Between Clamps, L (mm)	90	150	150
Width, b (mm)	30	25	25
Thickness, d (mm)	3.5	3	3.1
Applied Load, P (N)	25000	25000	25000
Tensile Strength, S1 = P/(b*d) (MPa)	238.10	333.33	322.58
FEA Stress, S2 (MPa)	238.21	333.33	322.60
Hand calc. vs. FEA, Error = S1/S2-1 (%)	**-0.05**	**0.00**	**-0.01**
Section Elastic Modulus, E (MPa)	3300	3300	3300
Tensile Strain, e = S1/E	7.22E-02	1.01E-01	9.78E-02
Disp., x1 = e * L (mm)	6.49	15.15	14.66
FEA Disp., x2 (mm)	6.40	15.04	14.56
Hand calc. vs. FEA, Disp. Error = x1/x2-1 (%)	**1.43**	**0.74**	**0.71**

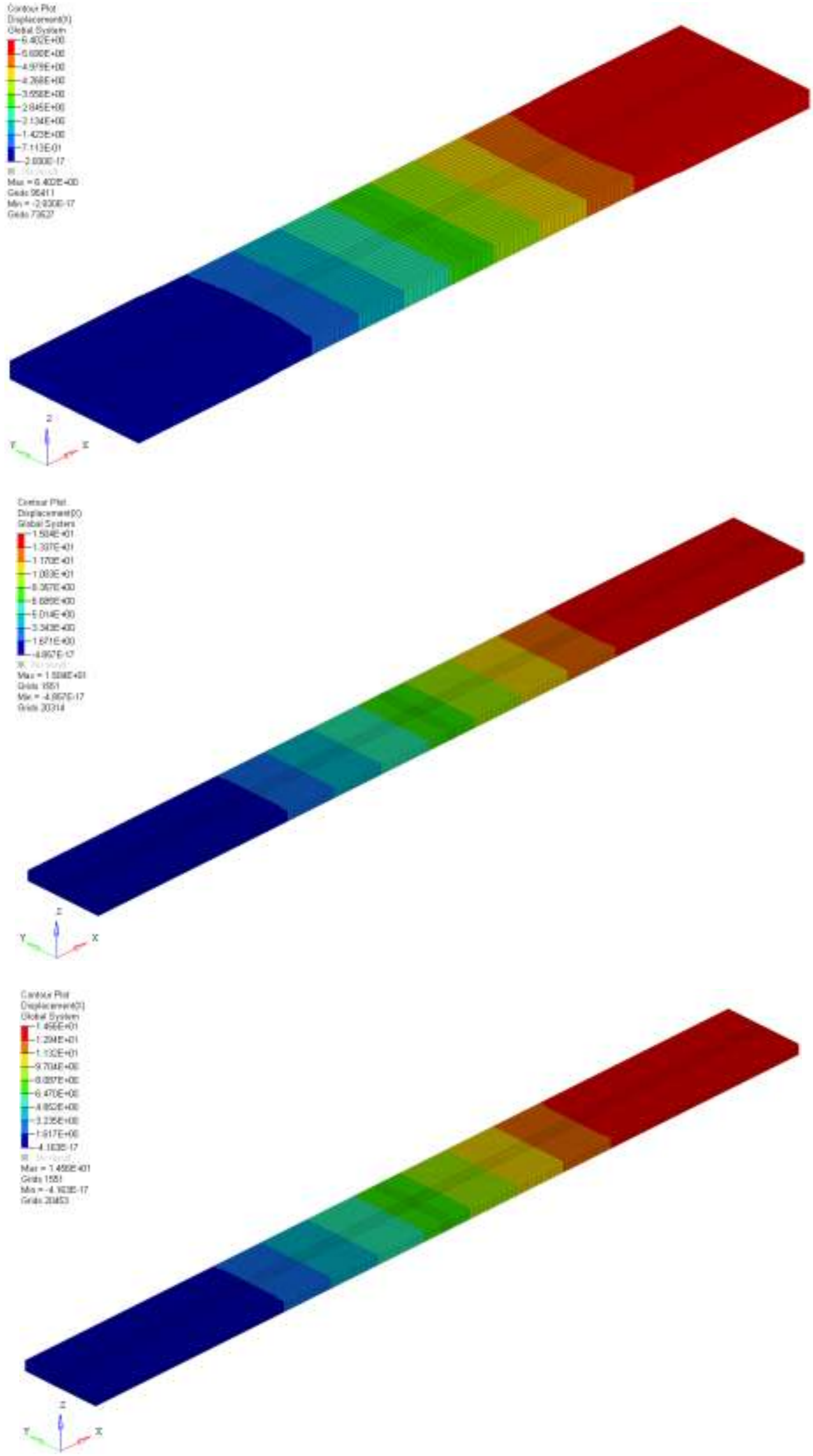

Figure 8.8: Tensile test BC validation using neat resin property, X-Displacement (mm) fringe; FML01 (top), FML02 (middle) and FML03 (bottom)

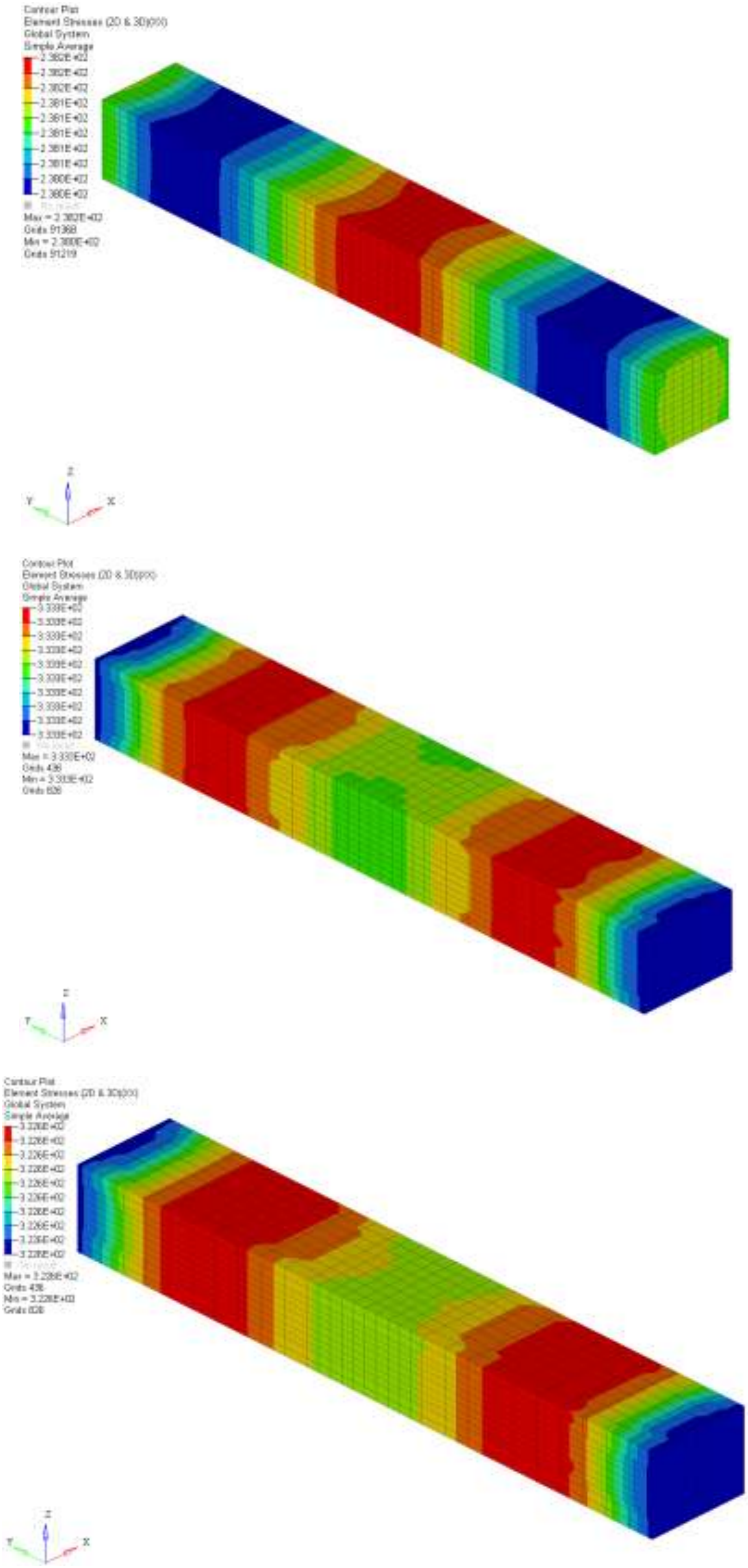

Figure 8.9: Tensile test BC validation using neat resin property, X-Stress (MPa) fringe; FML01 (top), FML02 (middle) and FML03 (bottom)

For flexure test BC validation, the fringe plots of displacement and mid-span stress tensor in the X-direction from the linear static analysis with neat resin properties for FZ = -4 kN applied load are presented in Figure 8.10 and Figure 8.11 respectively. The correlation of hand calculations and FEA is given in Table 8.5. Given the fact that the three point bending test involves a contact friction between the rollers and the specimen, the flexure test validation model results are deemed of acceptable behaviour. The FEA results are within reasonable deviation from the analytical calculations. This validates the BC and mesh density adopted for flexure test FEA.

Table 8.5: Flexure test BC validation using neat resin property, FEA vs. Theory

FLEXURE TEST	**FML1**	**FML2**	**FML3**
Material	Epoxy	Epoxy	Epoxy
FEM No.	M102	M202	M302
Length (mm)	150	120	120
Support Roller Span, L (mm)	100	100	100
Width, b (mm)	30	30	30
Thickness, d (mm)	3.5	3	3.1
Applied Load, F (N)	4000	4000	4000
Flexure Strength, S1 = $3*F*L/(2*b*d^2)$ (MPa)	1632.65	2222.22	2081.17
FEA Stress, S2 (MPa)	1760.00	2362.00	2220.00
Hand calc. vs. FEA, Error = S1/S2-1 (%)	**-7.24**	**-5.92**	**-6.25**
Section Elastic Modulus, E (MPa)	3300	3300	3300
Disp., x1 = $F*L^3/(48*E*I)$ (mm)	235.592	374.111	339.062
FEA Disp., x2 (mm)	225.000	355.600	322.600
Hand calc. vs. FEA, Disp. Error = x1/x2-1 (%)	**4.71**	**5.21**	**5.10**

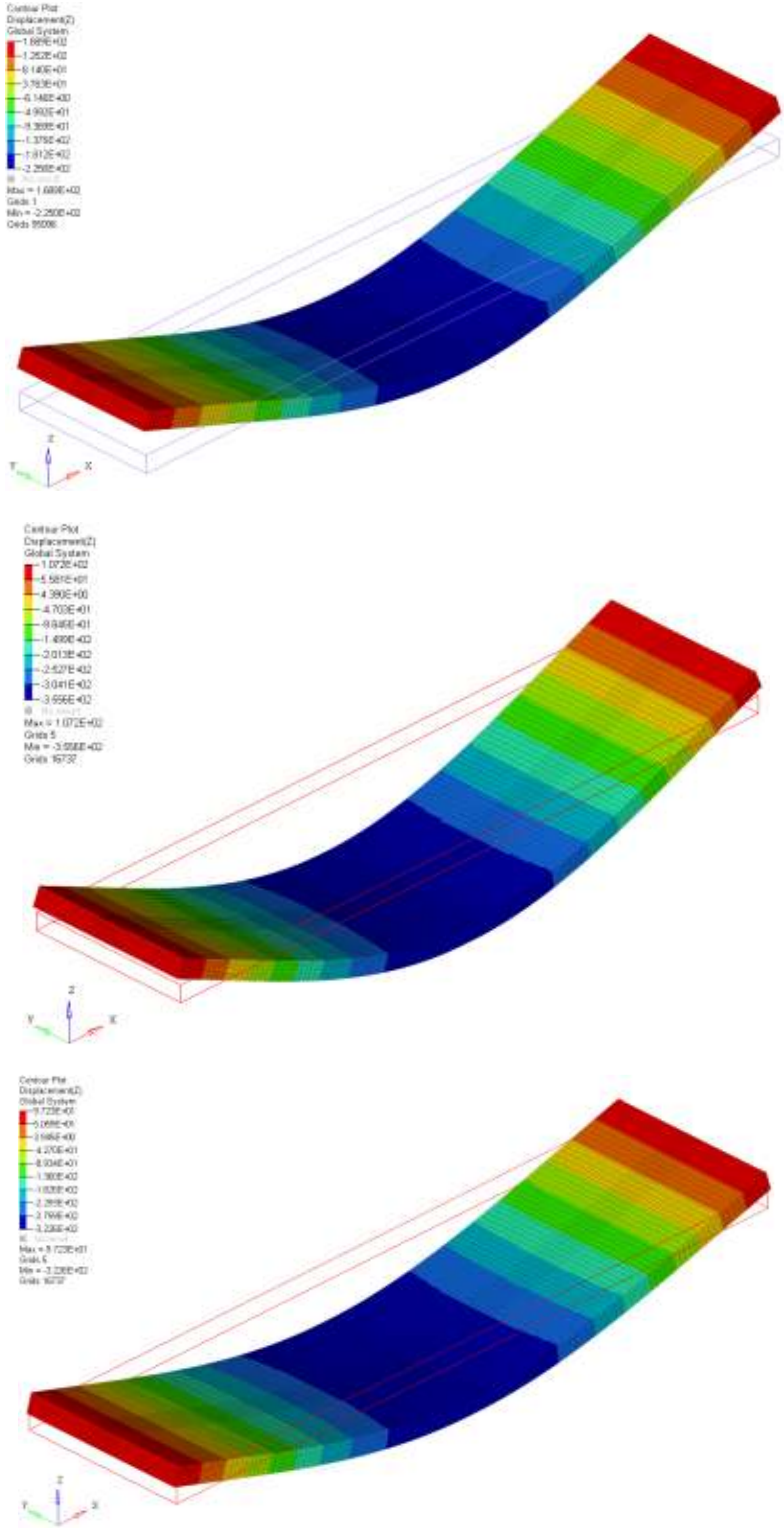

Figure 8.10: Flexure test BC validation using neat resin property, Deformation with Z-Displacement (mm) fringe; FML01 (top), FML02 (middle) and FML03 (bottom)

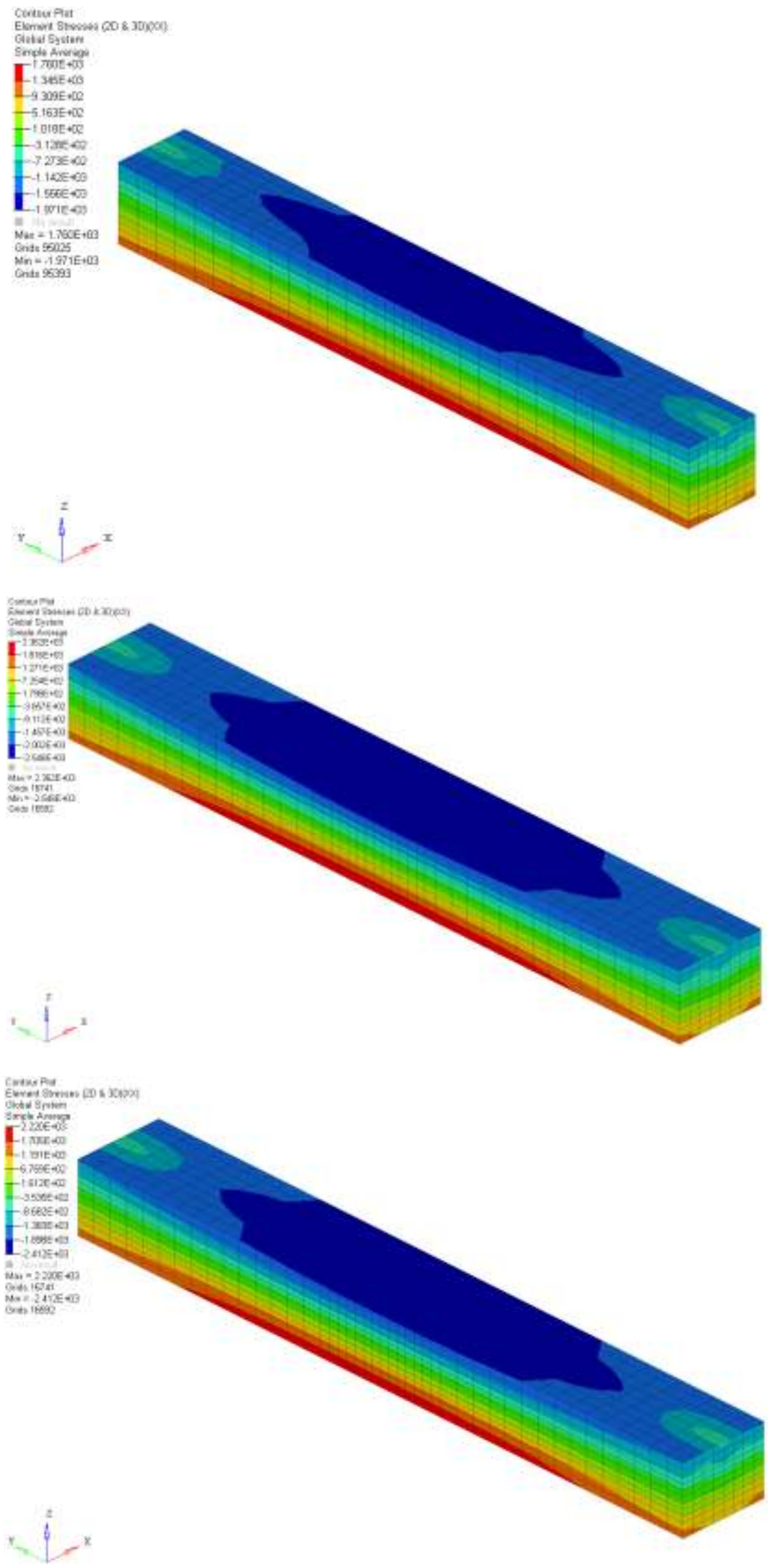

Figure 8.11: Flexure test BC validation using neat resin property, X-Stress (MPa) fringe; FML01 (top), FML02 (middle) and FML03 (bottom)

8.6. TENSILE TEST VERIFICATION: FML COMPOSITES

Using the validated boundary conditions as presented in earlier sections, the FML composite test specimen models are run using the test failure load (i.e. peak load at failure) to verify whether the experimental results are as expected. The peak load at failure is calculated using the Stress vs. Strain test data and the cross section area of the specimen. As the cross section consists of multiple materials such as E-Glass, HS-Carbon and Aluminium, the correlation of test results is undertaken using the tensile stresses in those layers of the FML composite. Based on the constant strain throughout the cross-section and its constituent layers due to the validity of perfect bond between the layers, the layer stresses can be calculated from the test failure strength and the elastic modulus of FML composite [7]. The membrane elastic modulus of FML composite is obtained using PCOMP composite material definition that is available within MIDAS NFX FEA software.

The X-Displacement from the test is calculated using the length of the specimen between the clamps for the equivalent strain calculated from the tensile test failure strength. The fringe plots of displacement and mid-span stress tensor in the X-direction from the linear static analysis of FML composite tensile test specimen models are presented in Figure 8.12 and Figure 8.13 respectively. As the stiffness of UD HS-Carbon layers are roughly 85% more than the Aluminium layer (i.e. 130000 MPa/70000 MPa), the X-Stress in HS-Carbon layers as obtained from the FEA are higher in same proportion than that of Aluminium layers as expected. The correlation of test results with FEA simulations is given in Table 8.6. The FEA results indicate that the experimental tests behaved well as expected both in terms of the elongation and the peak stress locations and their magnitudes. The X-Stress in the aluminium layers as obtained from the tensile tests are ~3% lesser than that as predicted by the FEA. These FEA results verify the tensile tests undertaken for the FML composites.

Table 8.6: Tensile test verification of FML composites, Test vs. FEA

TENSILE TEST	FML01	FML02	FML03
Test Specimen No.	4	3	3
FEM No.	M111	M211	M311
Length (mm)	150	250	250
Distance Between Clamps, L (mm)	90	150	150
Width, b (mm)	30	25	25
Thickness, d (mm)	3.5	3	3.1
Test Tensile Strength, S (MPa)	186.35	494.80	357.60
Section Elastic Modulus, E (MPa)	30285	86685	52775
FEA Applied Load, P = S*b*d (N)	19567	37110	27714
Tensile Strain, e = P/(E*b*d)	6.15E-03	5.71E-03	6.78E-03
Test Stress at Alu. Layer, S1 = 70000 * e (MPa)	430.73	399.56	474.31
FEA Stress at Alu. Layer, S2 (MPa)	443.80	401.60	482.30
Test vs. FEA, Stress at Alu. Error = S1/S2-1 (%)	**-2.95**	**-0.51**	**-1.66**
Test Disp., x1 = e * L (mm)	0.554	0.856	1.016
FEA Disp., x2 (mm)	0.551	0.855	1.015
Test vs. FEA, Disp. Error = x1/x2-1 (%)	**0.52**	**0.18**	**0.14**

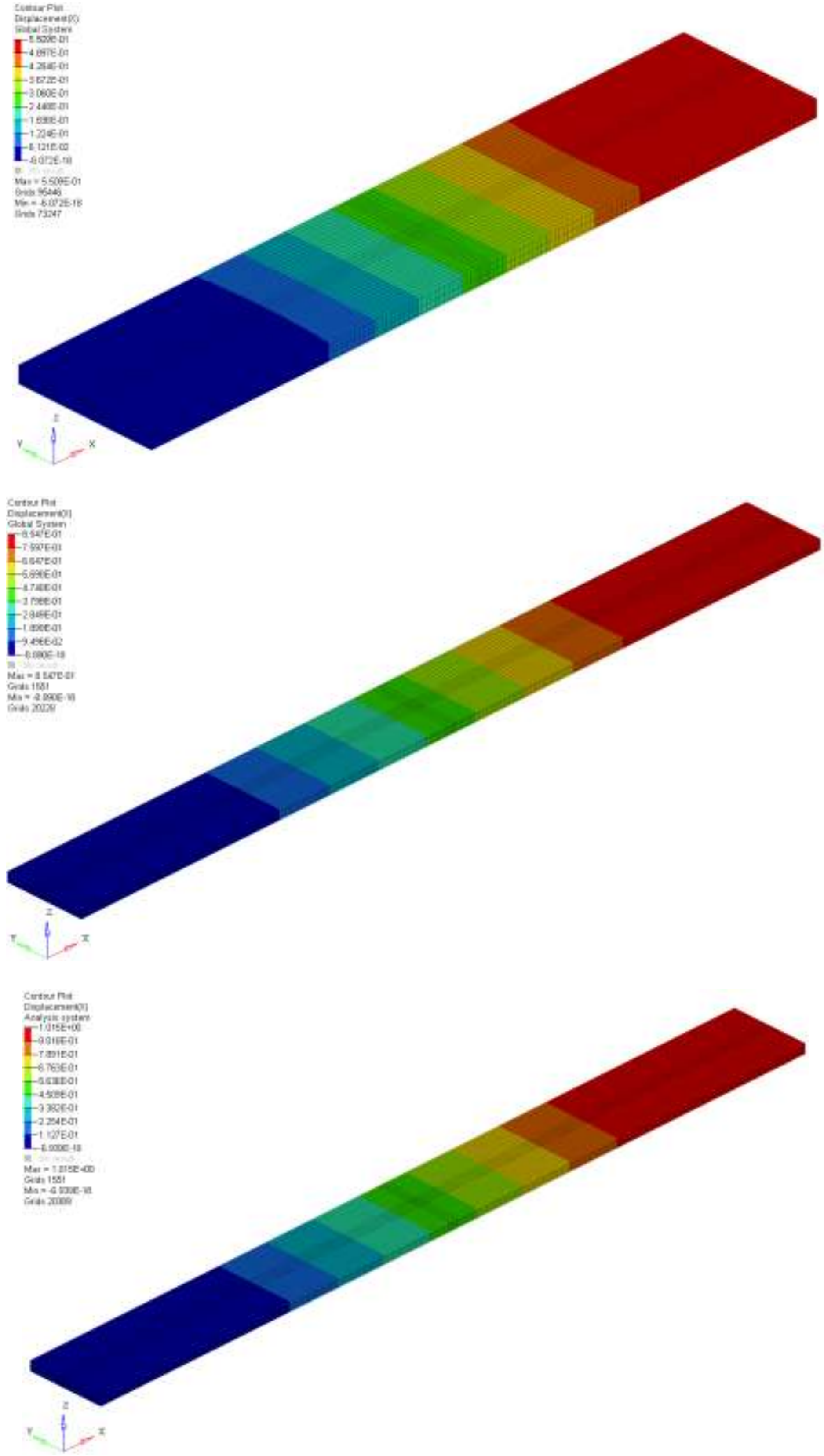

Figure 8.12: FML tensile test verification, X-Displacement (mm) fringe; FML01 (top), FML02 (middle) and FML03 (bottom)

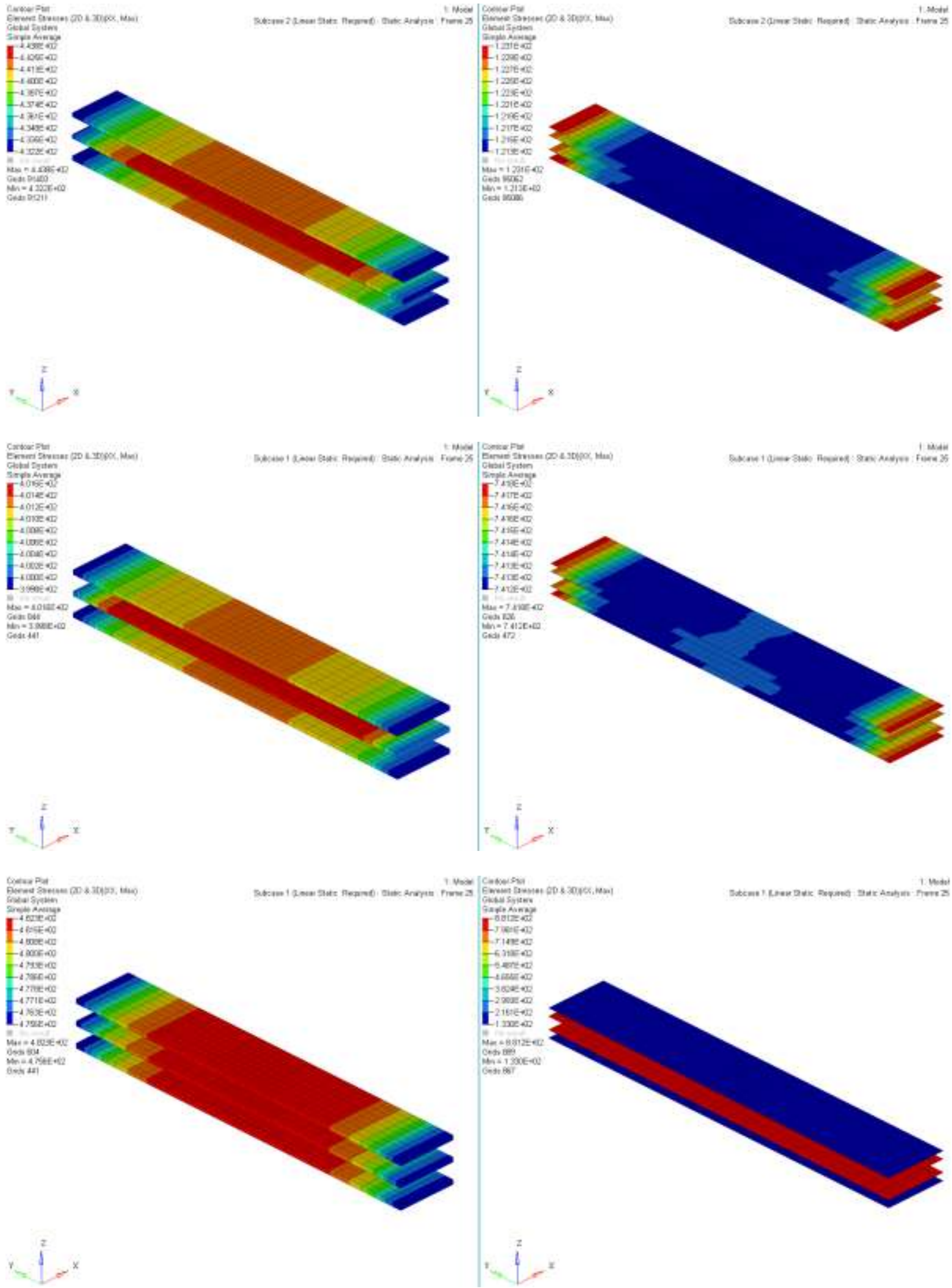

Figure 8.13: FML tensile test verification, X-Stress (MPa) fringe in AL 1100 (left) and Composites (right); FML01 (top), FML02 (middle) and FML03 (bottom)

8.7. FLEXURE TEST VERIFICATION: FML COMPOSITES

Using the validated boundary conditions for flexure test as presented in earlier sections, the FML composite test specimen models are run using the test failure load (i.e. peak load at failure) to verify whether the experimental results are as expected. As the cross section consists of multiple materials such as E-Glass, HS-Carbon and Aluminium, the correlation of test results is undertaken using the flexure stress (X-Stress) in those layers of the FML composite. Based on the linear and stiffness proportionate variation of strain throughout the cross-section and its constituent layers due to the validity of pure bending condition under flexure test as shown in Figure 8.14, the layer stresses can be calculated from the strain variation and the section flexural modulus of FML composite [8]. The flexural modulus of FML composite is obtained using PCOMP composite material definition that is available within MIDAS NFX FEA software.

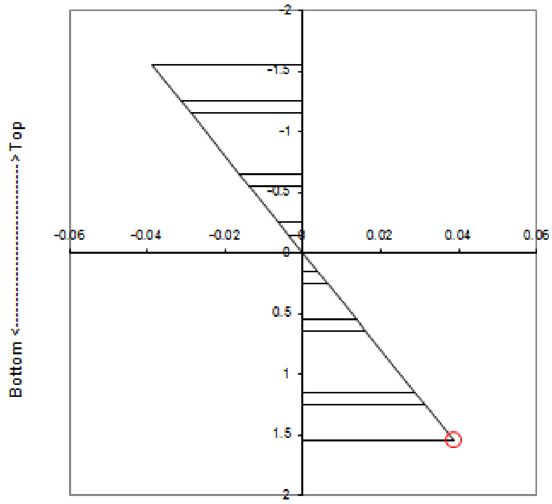

Figure 8.14: Flexural strain variation for three point bending of FML composite specimen, (e.g. FML03)

The Z-Displacement from the test is calculated using the distance between the support rollers (i.e. simply supported beam shear force and moment diagrams) and the peak load at failure. The fringe plots of Z-displacement and mid-span stress tensor in the X-direction from the linear static analysis of FML composite flexure test specimen models are presented in Figure 8.15 and Figure 8.16 respectively. The correlation of test results with FEA simulations is given in Table 8.7. The FEA results indicate that the experimental tests behaved well as expected both in terms of the elongation and the peak stress locations and their magnitudes. The X-Stress in the aluminium layers as obtained from the tensile tests are ~7% higher (mixed E-Glass and HS-Carbon) than that as predicted by the FEA. Equally, the Z-Displacement from the tests is about 16% less than the FEA prediction. There are a number of reasons behind these differences between the test and FEA results. Suggestions for improvement in FEA predictions are outlined in the summary section. These FEA results verify the flexural tests undertaken for the FML composite specimens.

Table 8.7: Flexure test verification of FML composites, Test vs. FEA

FLEXURE TEST	**FML01**	**FML02**	**FML03**
Test Specimen No.	1	2	2
FEM No.	M112	M212	M312
Length (mm)	150	120	120
Support Roller Span, L (mm)	100	100	100
Width, b (mm)	30	30	30
Thickness, d (mm)	3.5	3	3.1
Test Flexure Load, F (N)	3382	3870	3424
Section Flexural Modulus, E (MPa)	39383	80175	46018
Extreme Layer Stress, $S0 = 3*F*L/(2*b*d^2)$ (MPa)	1380.41	2150.00	1781.48
Test Stress at Alu. Layer, S1 = S0 * 70000/E (MPa)	2453.56	1877.15	2709.88
FEA Stress at Alu. Layer, S2 (MPa)	2348.00	1899.00	2533.00
Test vs. FEA, Stress at Alu. Error = S1/S2-1 (%)	**4.50**	**-1.15**	**6.98**
Test Disp., $x1 = F*L^3/(48*E*I)$ (mm)	16.691	14.898	20.813
FEA Disp., x2 (mm)	19.260	17.870	22.960
Test vs. FEA, Disp. Error = x1/x2-1 (%)	**-13.34**	**-16.63**	**-9.35**

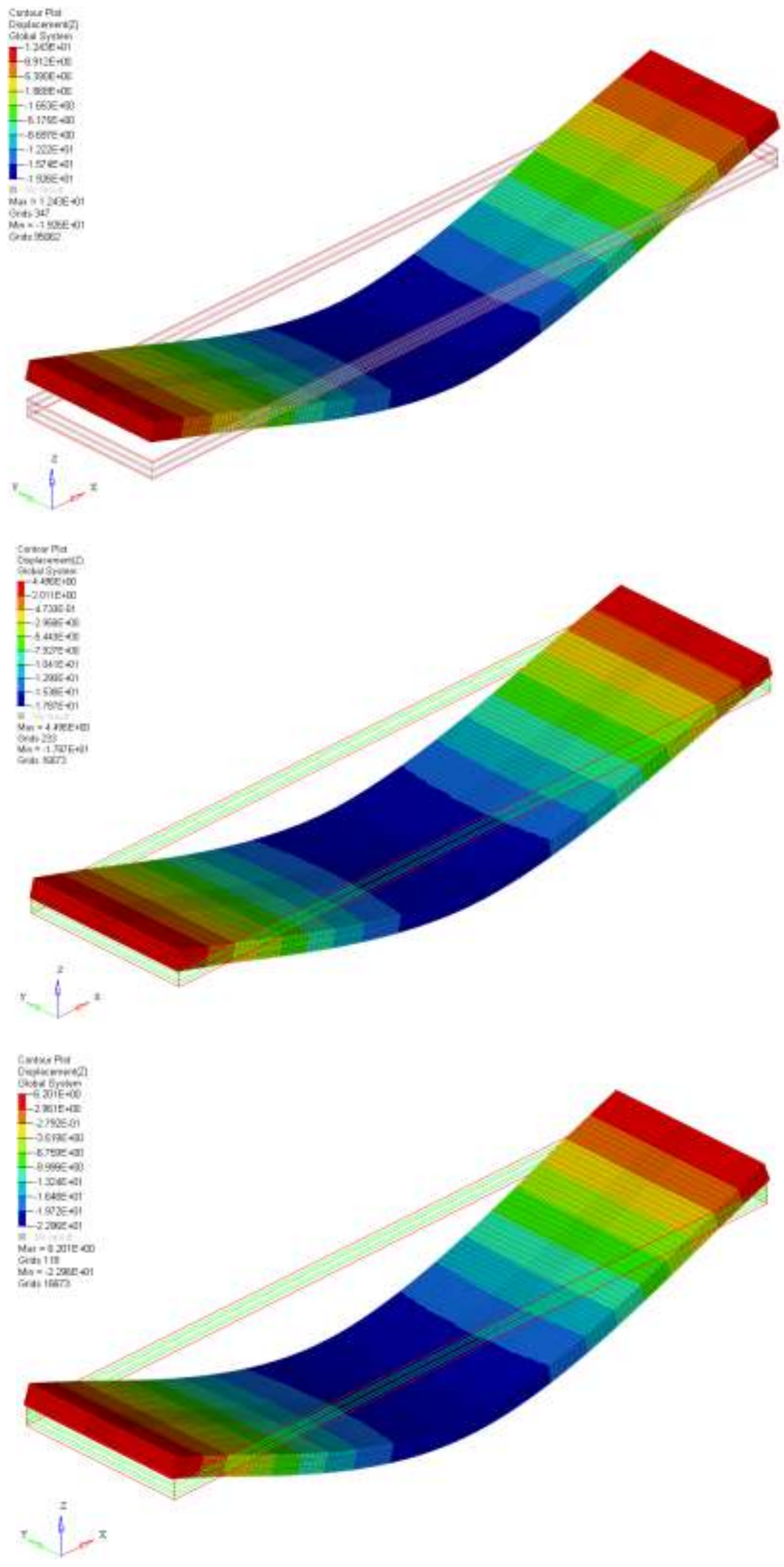

Figure 8.15: FML flexure test verification, Deformation with Z-Displacement (mm) fringe; FML01 (top), FML02 (middle) and FML03 (bottom)

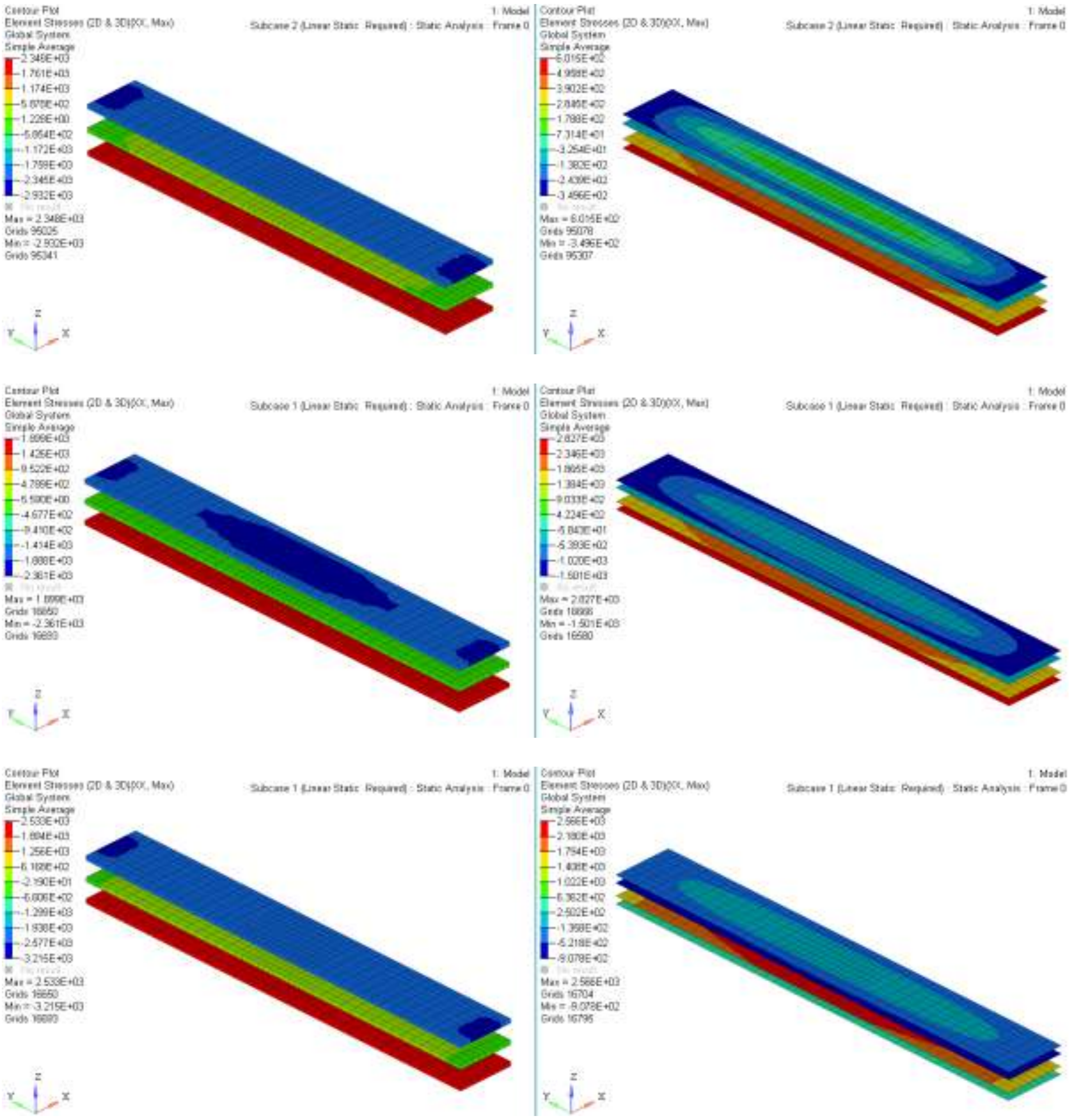

Figure 8.16: FML flexure test verification, X-Stress (MPa) fringe in AL 1100 (left) and Composites (right); FML01 (top), FML02 (middle) and FML03 (bottom)

8.8. TEST VS. FEA RESULTS SUMMARY

Detailed finite element modelling and simulations of experimental test (tensile and flexure) loading and boundary conditions for all the 3 FML composites confirm that the structural behaviour and peak stresses in the Aluminium layer are in good agreement with the FEA predictions. The comparisons of tensile and flexure test results with FEA predictions are shown in Figure 8.17 and Figure 8.18 respectively.

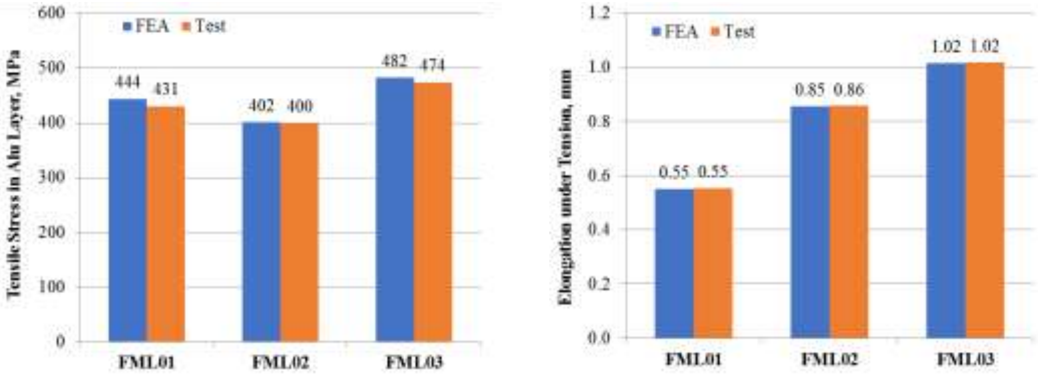

Figure 8.17: FML tensile test verification – Test vs. FEA

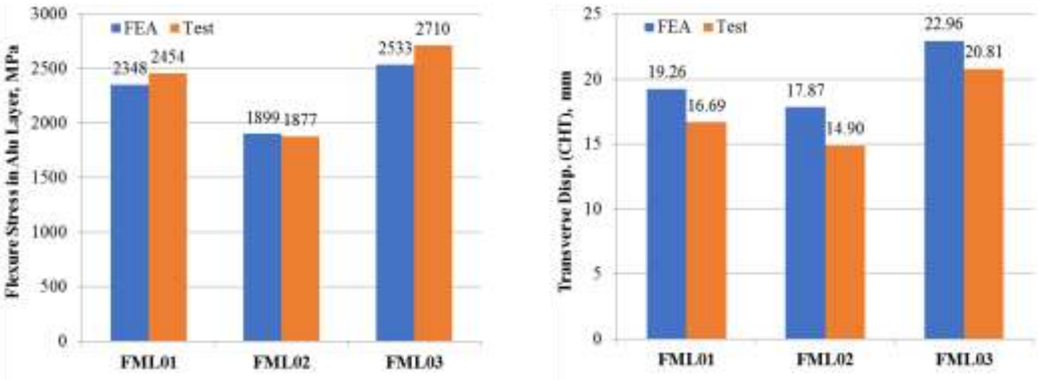

Figure 8.18: FML flexure test verification – Test vs. FEA

Tensile test simulations are within 3% error margins. Flexure test simulations produced higher error margins in the order of 7% for flexure stress and 16% for transverse displacement. These differences are mainly due to idealisation of cured ply thickness and bond line of the finished specimen in the FEA as well as nodal constraints based simply supported boundary conditions. In particular, if the frictional contact between the support & loading rollers with the test specimen are modelled, the Z-Displacement from FEA should be lesser than the current predictions. The X-Stress in Aluminium layers are the average stress within the 3D BRICK elements. If the extreme fibre stresses are extracted through using nodal stresses, then these FEA stress values could be slightly higher. The FEA results are also influenced by the Poisson effects [9] due to the mixed material FML composite specimen modelling comprising UD, Woven composites and isotropic stiff Aluminium layer. However, the applied boundary conditions have demonstrated that there is a little Poisson effects and over constraint based on the error margins noticed.

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