FIBRE-REINFORCED POLYMER (FRP) COMPOSITES FOR STRENGTHENING AND STIFFENING OF STEEL BRIDGE MEMBERS

Presentation to BOF Meeting
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Outline of presentation

- Objectives
- Test programme
- FRP strengthening of specimens
- Finite element, FE, analyses
- Comparison and discussion of results
- Conclusions

Objectives

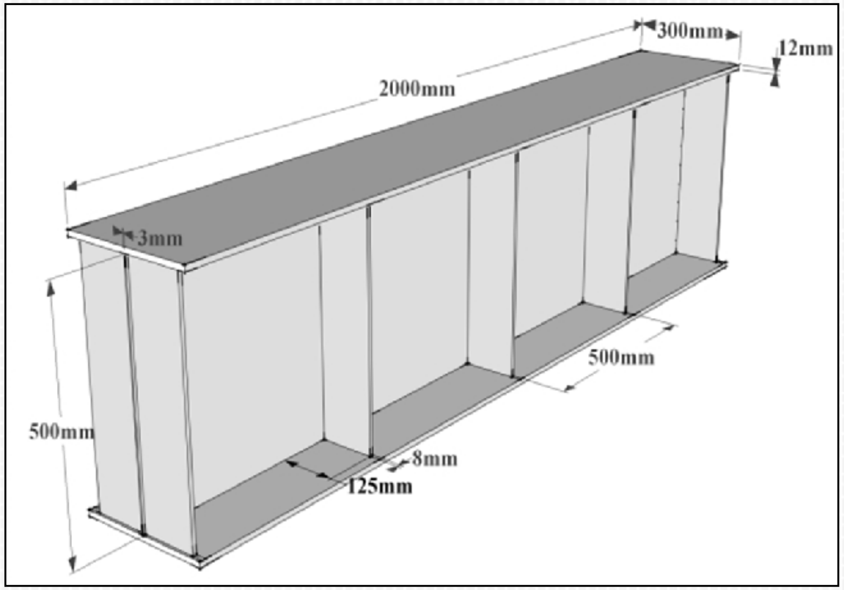
- To investigate the use of carbon and glass fibre reinforced polymer (FRP) composites and fabrics to strengthen and stiffen steel beams with slender web panels
- To carry out experimental investigations of un-strengthened and FRP-strengthened steel beams
- To carry out studies of un-strengthened and FRP-strengthened steel beams using FE modelling
- To use test and FEA results to suggest improvement, if any, in the existing design guidance available in CIRIA Report No. C595 for use in practice

Test programme

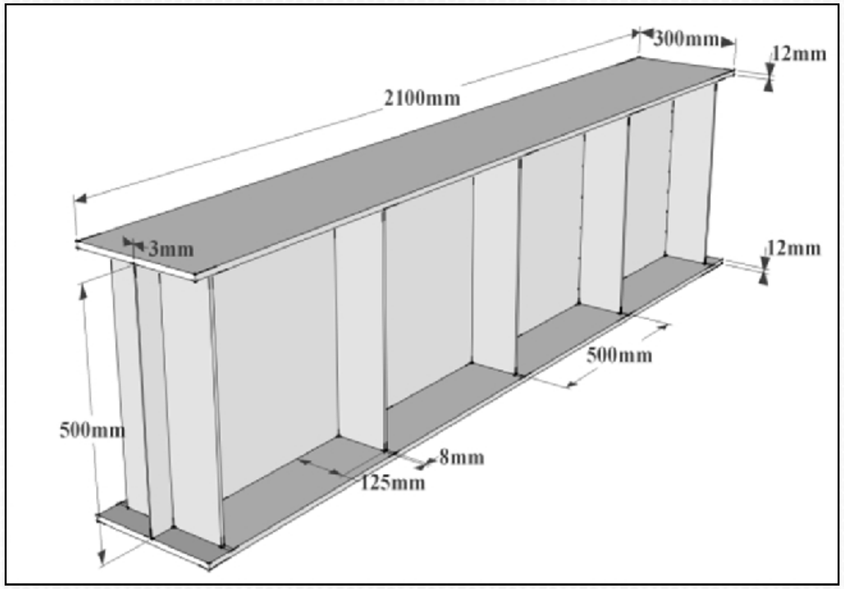
Steel beams (series S1 and S2)

The beams in series S1 and S2 were similar in construction with a small variation in lengths. The length, 2100 mm, of S2 beams was made 1.05 times that, 2000 mm, of S1 beams to avoid development of plastic hinges in the external steel stiffeners

S1 beam used for specimens B1 to B4



S2 beam used for specimens B5 to B8



Material testing of steel

- S275 grade of steel was used in the fabrication of S1 and S2 beams

- The yield and ultimate tensile strengths of the steel used in two series of the beams were measured by the tensile testing in accordance with the British/ European Standards ISO 6892-1, 2009

- The tested values are given in Table 1

Table 1: Measured properties of steel used in S1 and S2 beams

Beam series	Yield strength of steel (MPa)			Ultimate strength of steel (MPa)		
	Flange	Web	Stiffener	Flange	Web	Stiffener
S1 beams	322	274	308	446	375	463
S2 beams	330	353	334	440	473	450
Ratio of S2 to S1	1.02	1.29	1.08	0.99	1.26	0.97

FRP strengthening of specimens

Methods of FRP strengthening

Two methods were used for FRP strengthening of the test specimens

- **GFRP pultruded section strengthening**

The test specimens B2, B5, B6 and B8 were strengthened using glass fibre reinforced polymer, GFRP, pultruded T-sections as additional stiffeners either on one or both sides of the end web panels and were grouped as Group G2 specimens

- **FRP fabric strengthening**

The test specimens B3, B4 and B7 were strengthened using four or eight layers of FRP carbon or glass fabric to one side of the end web panels and were grouped as Group G3 specimens

FRP strengthening of specimens (cont'd)

GFRP pultruded section strengthening

In GFRP pultruded section strengthening, T-section stiffeners were cut from GFRP T or I section profiles

- T-section GFRP profiles were manufactured by Strongwell Corporation, USA and supplied by Pipex Limited, UK
- I-section composite profiles were manufactured and supplied by DURA Composites Limited, UK
- Properties of the GFRP T and I-sections are given in Table 2

Table 2: Properties of GFRP pultruded sections

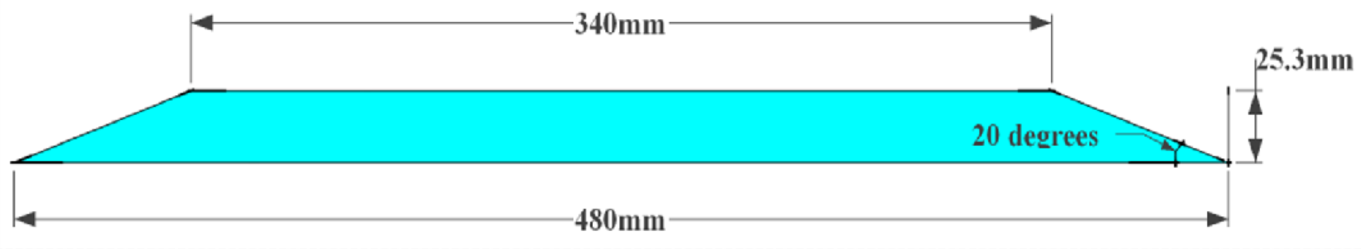
Name of property	T-section	I-section
Tensile strength (MPa)	400**	290-760*
Tensile modulus of elasticity (GPa)	36**	36*
Poisson's Ratio	0.15*	0.15*
Density (Kg/m^3)	1700*	1600-2100*
Glass transition temperature T_g (^oC)	*	*
GFRP sections used for specimen(s)	B2	B5, B6 & B8
* Value supplied by manufacturer ** Test values obtained by authors		

FRP strengthening of specimens (cont'd)

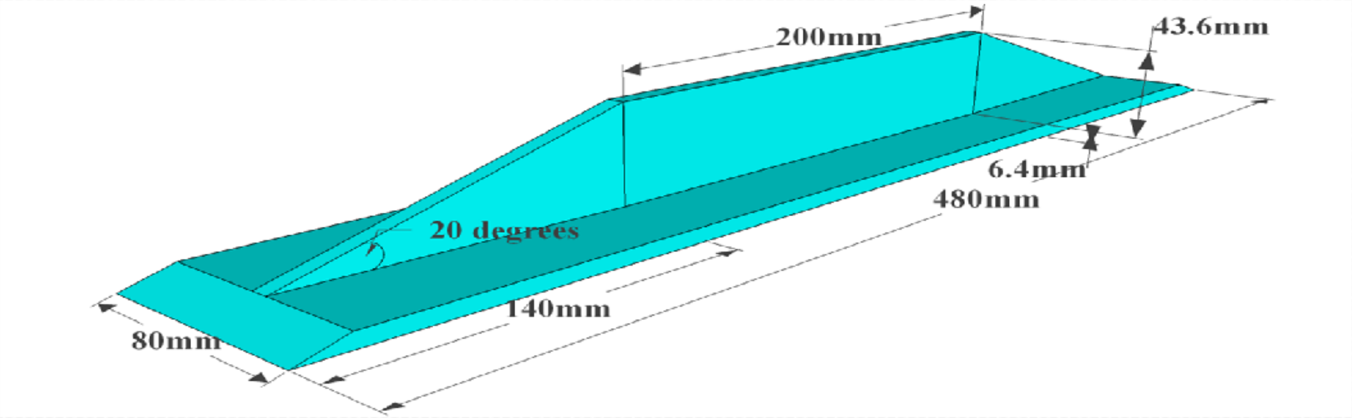
Tapering ends of GFRP stiffener

To reduce the shear stresses in the adhesive at ends of the GFRP pultruded section stiffeners in the specimens B2 and B5, the ends were tapered to an angle of approximately 20 degrees

Longitudinal section of tapered GFRP stiffener of specimen B2



Side view of tapered GFRP stiffener of specimen B5



FRP strengthening of specimens (cont'd)

Carbon and glass fabric strengthening

- **In FRP fabric strengthening, the fabric layers were cut from carbon and glass fabric sheets. Both fabrics had three-axial layup of woven fibres and were manufactured and supplied by Walker Technical Resources Limited, Aberdeen, UK**

- **The properties of the carbon and the glass fabric sheets as provided by the manufacturer are given in Table 3**

Table 3: Properties of carbon and glass fabrics

Name of property	Carbon fabric	Glass fabric
Tensile strength (MPa)	530	104
Tensile Modulus of elasticity (GPa)	36	13
Tensile Strain at failure (%)	1.5	1.27
Shear Modulus (GPa)	3.3	2
Poisson's Ratio	0.32	0.27
Glass transition temperature T_g (^oC)	120	120
Fabric used for specimen(s)	B3	B4 & B7

Test specimens

Grouping of test specimens

Based upon the type of FRP strengthening provided to the test panels, the specimens were divided into three groups namely G1, G2 and G3

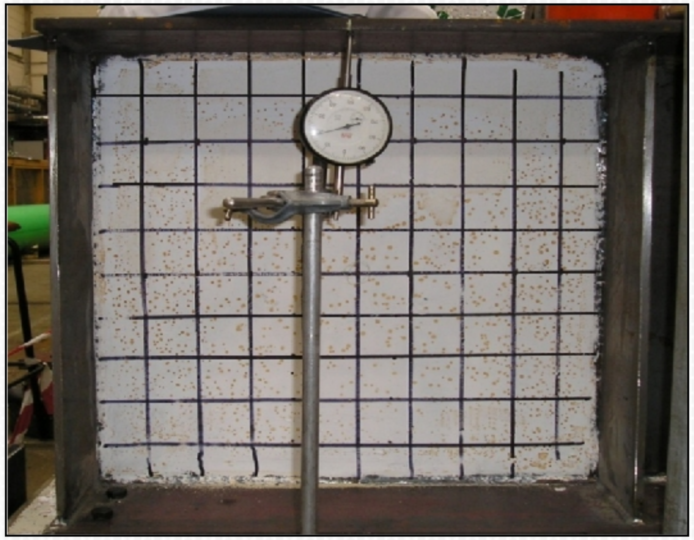
Specimen group	Group description	Specimen/ model No	Beam series No
G1	Un-strengthened control specimen/ FE model	B1	S1
		B9	S2
G2	Glass FRP pultruded section strengthened specimens	B2	S1
		B5	S2
		B6	S2
		B8	S2
G3	FRP fabric strengthened specimens	B3	S1
		B4	S1
		B7	S2

Test specimens (cont'd)

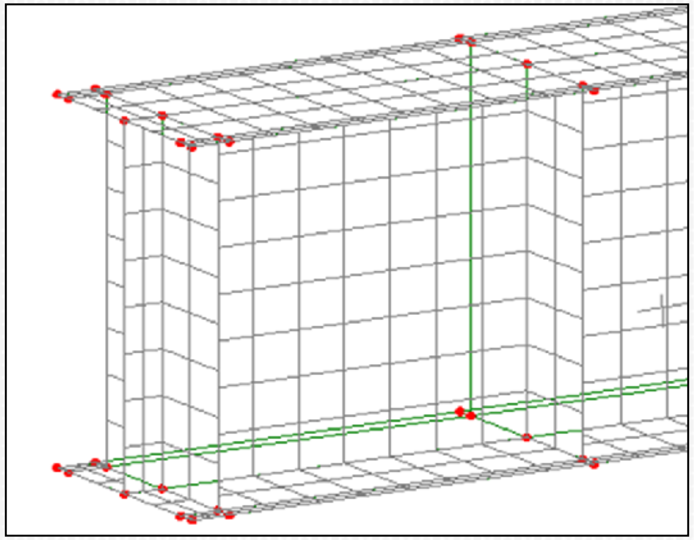
Group G1: Un-strengthened control specimens

Specimen/ model No	Beam series No	Details of FRP-strengthening
B1	S1	None
B9	S2	None

Control specimen B1



Control model B9



Note: After a good agreement between the test and the FEA results of control specimen B1 for S1 beams, an FE model B9 was used as the control for S2 beams instead of a separate control test specimen

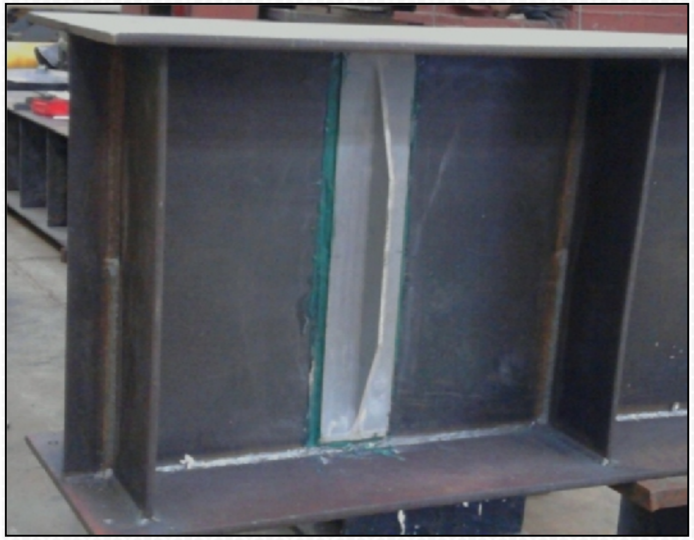
Test specimens (cont'd)

Group G2: GFRP pultruded section strengthened specimens

Specimen No	Beam series No	Details of FRP-strengthening
B2	S1	Two vertical GFRP T-section stiffeners, one on each side of end web panel
B5	S2	One vertical GFRP T stiffener on one side of end web panel

GFRP-strengthened specimen B2

GFRP-strengthened specimen B5



Test specimens (cont'd)

Group G2: GFRP pultruded section strengthened specimens (cont'd)

Specimen No	Beam series No	Details of FRP-strengthening
B6	S2	One diagonal GFRP T stiffener on one side of end web panel
B8	S2	Two vertical GFRP T-section stiffeners, one on each side of web beneath the applied load in place … rs

GFRP-strengthened specimen B6

GFRP-strengthened specimen B8

Test specimens (cont'd)

Group G3: FRP fabric strengthened specimens

Specimen No	Beam series No	Details of FRP-strengthening
B3	S1	Four layers of carbon fabric on one side of end web panel
B4	S1	Eight layers of glass fabric on one side of end web panel
B7	S2	Four layers of glass fabric on one side of end web panel

Carbon fabric strengthened specimen B3

Glass fabric strengthened specimen B4

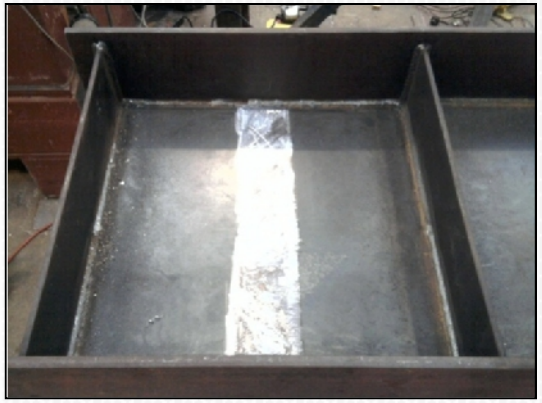
Glass fabric strengthened specimen B7

Surface preparation and bonding

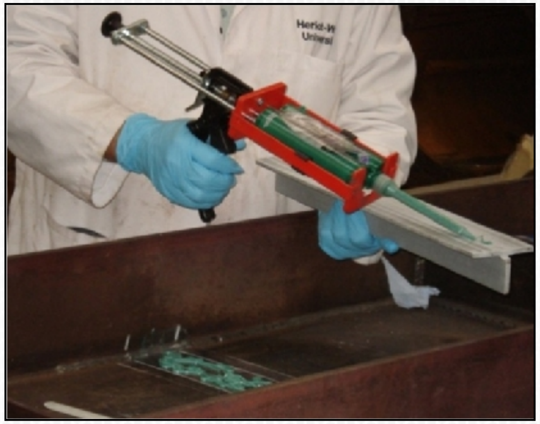
Group G2: GFRP pultruded section strengthened specimens

Grinding of steel surface

Prepared steel surface



Application of epoxy adhesive



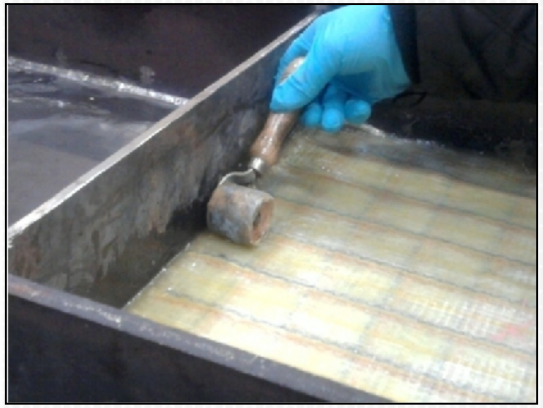
Clamping of GFRP stiffener in B2

Surface preparation and bonding

Group G3: FRP fabric strengthened specimens

Rolling with steel roller

Rolling with wooden roller

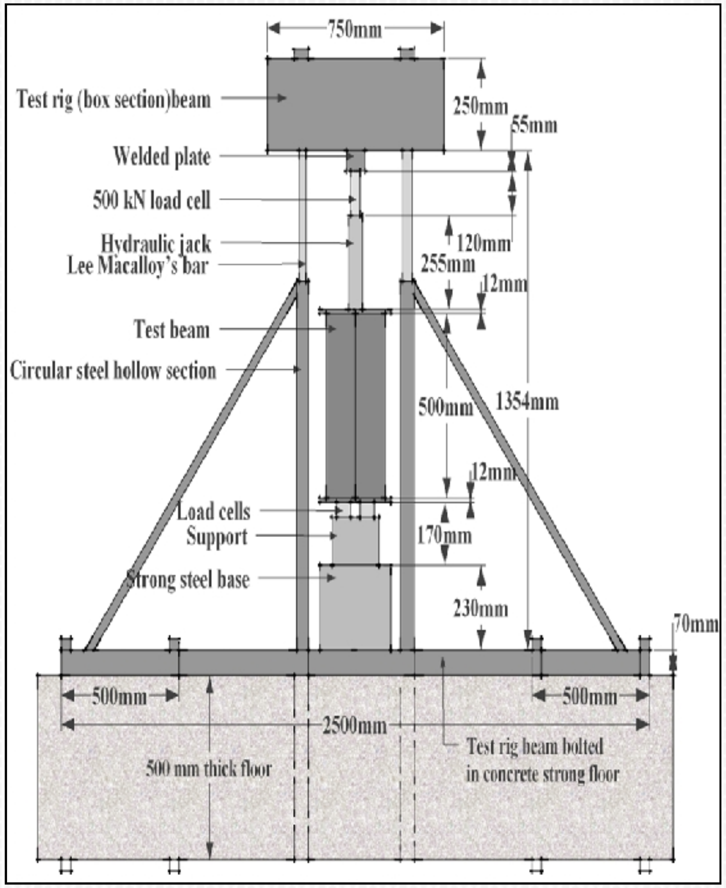


Placing of film coating in B7

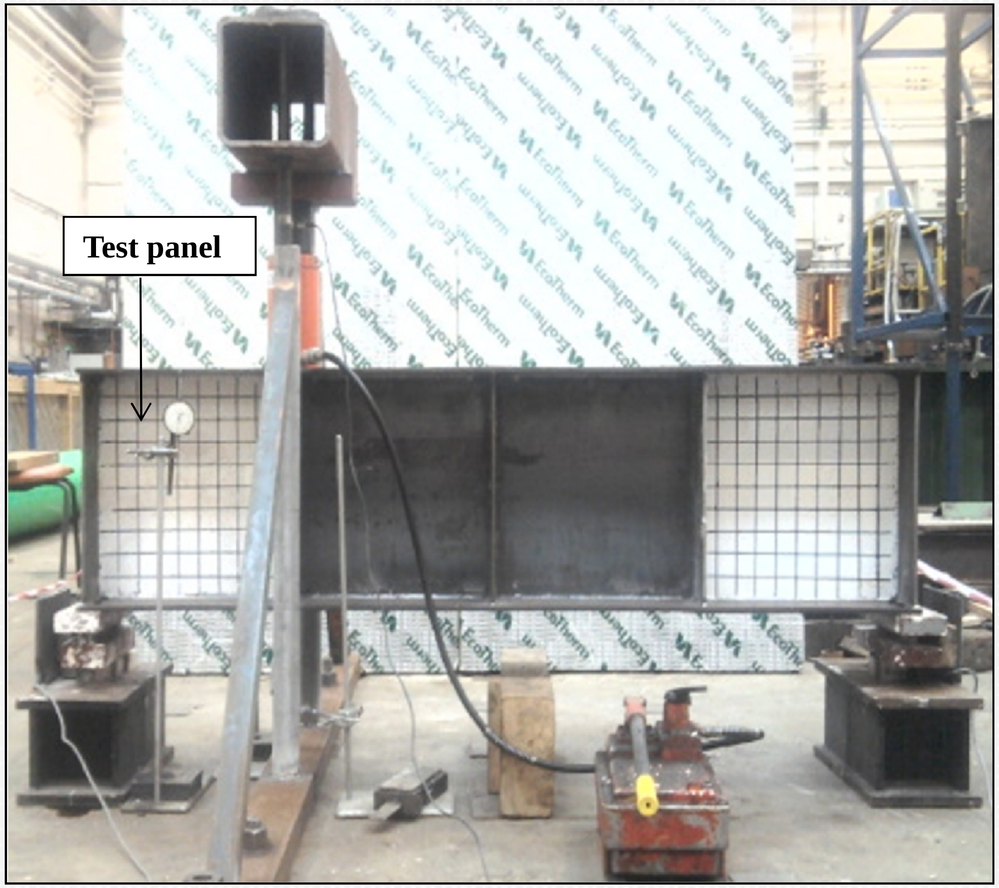
Clamping of glass fabric in B7

Loading & boundary conditions

Test rig



Testing of control specimen B1



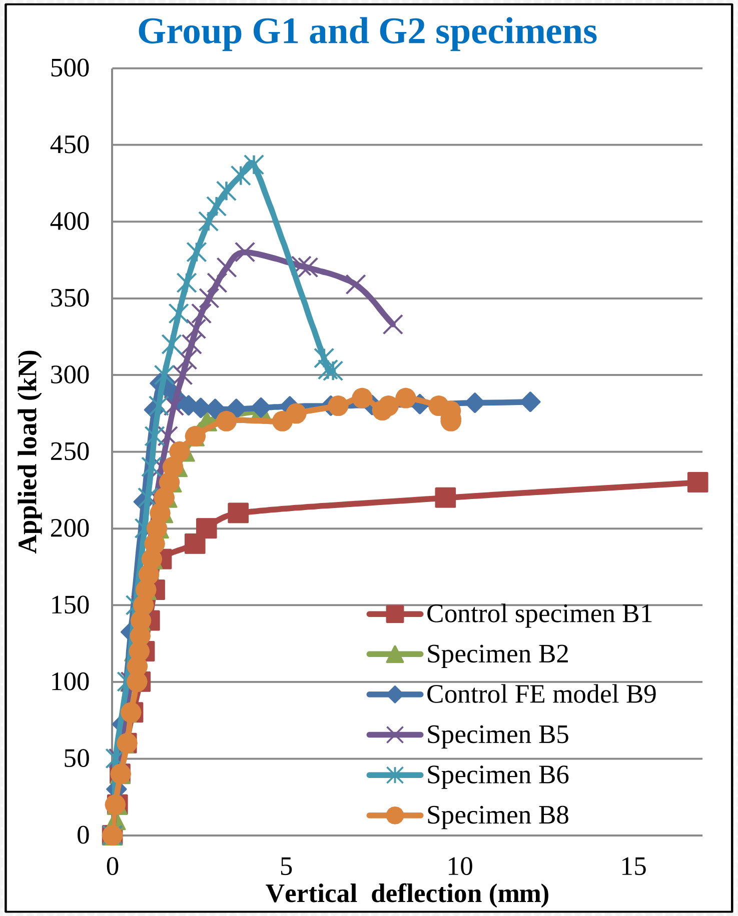
Tests Results

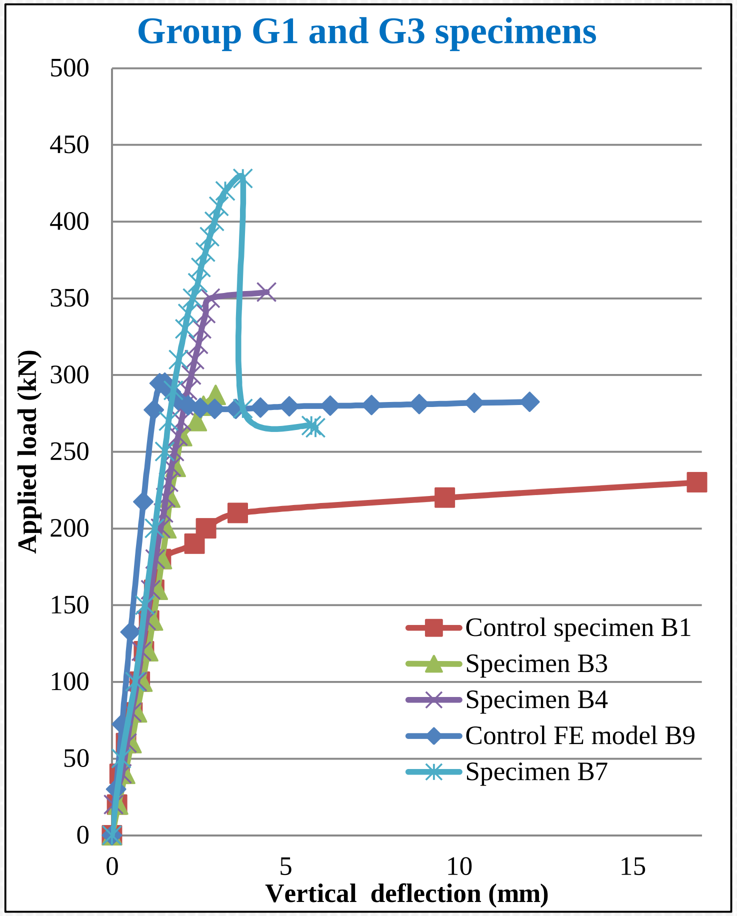
Ultimate loads and modes of failure of specimens

Specimen/ model No	Ultimate load (kN)	Ratio of ult. load of FRP-str. to control	Mode of failure
Group 1: Un-strengthened control specimens			
B1	230	---	Out-of-plane diagonal buckling of end web panel and plastic hinges in top flange and external steel stiffeners
B9	295	---	Out-of-plane diagonal buckling of end web panel and plastic hinges in top flange and external steel stiffeners
Group 2: GFRP pultruded section strengthened specimens			
B2	277	1.20	Two small out-of-plane diagonal buckles in steel web on both sides of GFRP stiffeners and plastic hinges
B5	380	1.29	Two out-of-plane diagonal buckles in steel web on both sides of the GFRP stiffener, delamination of GFRP and plastic hinges
B6	437	1.48	Out-of-plane diagonal buckle in steel web similar to that of B1, delamination of GFRP stiffener and plastic hinges
B8	285	0.97	Out-of-plane diagonal buckling of web panel, delamination of GFRP stiffener and plastic hinges
Group 3: FRP fabric strengthened specimens			
B3	287	1.25	Break down of carbon-steel bond, small out-of-plane diagonal buckling of web on steel side and plastic hinges
B4	354	1.54	Break down of glass-steel bond, small out-of-plane diagonal buckling of web on steel side and plastic hinges
B7	428	1.45	Break down of glass-steel bond, out-of-plane diagonal buckling of web on steel side and plastic hinges

Tests Results (cont'd)

Plots of applied load vs. vertical deflection at underside of beam beneath loaded stiffeners of test specimens



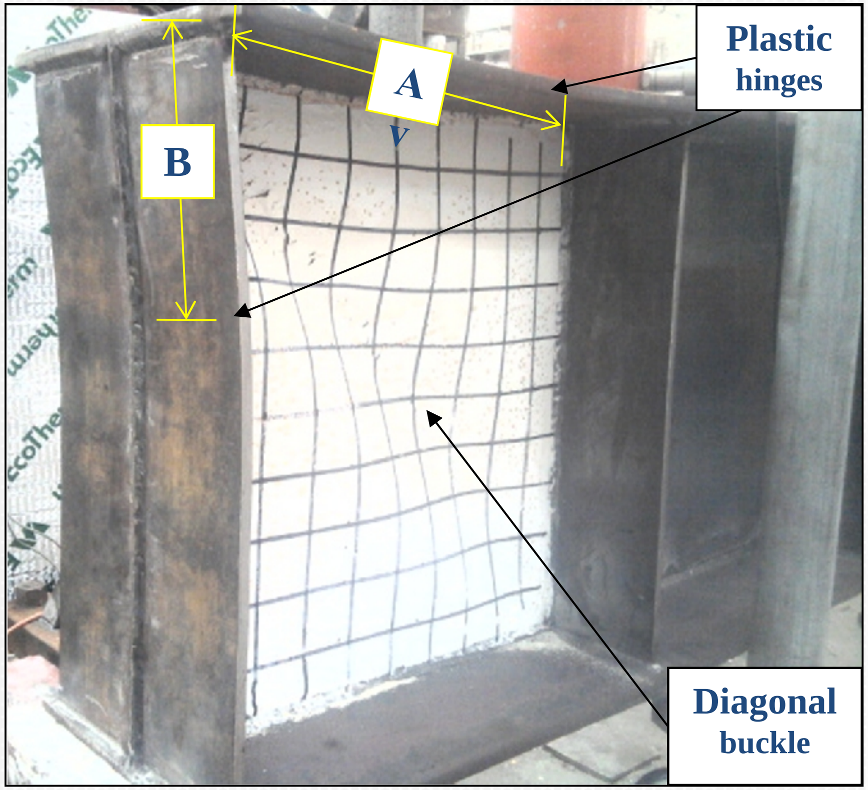


Tests Results (cont'd)

Failure of test specimens

All test specimens whether un-strengthened or FRP-strengthened failed in two stages

1. **Out-of-plane diagonal buckling in end web panel with or without a breakdown of bond between steel and FRP surfaces**
2. **Development of plastic hinges in top flange and external steel stiffeners**



Group No.	Specimen/ Model No.	Distance of plastic hinge from top corner of end web panel (mm)	
		Top flange (A)	End stiffener (B)
G1	B1	250	180
	B9	250	200
G2	B2	250	240
	B5	260	240
	B6	260	240
	B8	260	240
G3	B3	250	280
	B4	250	280
	B7	260	240

Finite element analyses (FEA)

- **Software used**

  LUSAS finite element programme version 14.3

- **Elements**

  Thin shell elements QSL8 for G1 and G2 specimens
  Thick shell elements QTS8 for G3specimens

- **Mesh sizes for web panels**

  8x8 mesh for QSL8 elements
  16x16 mesh for QTS8 elements

- **Material properties**

  Steel , GFRP pultruded sections and FRP fabrics were modelled as isotropic materials using their properties given in Tables 1, 2 and 3

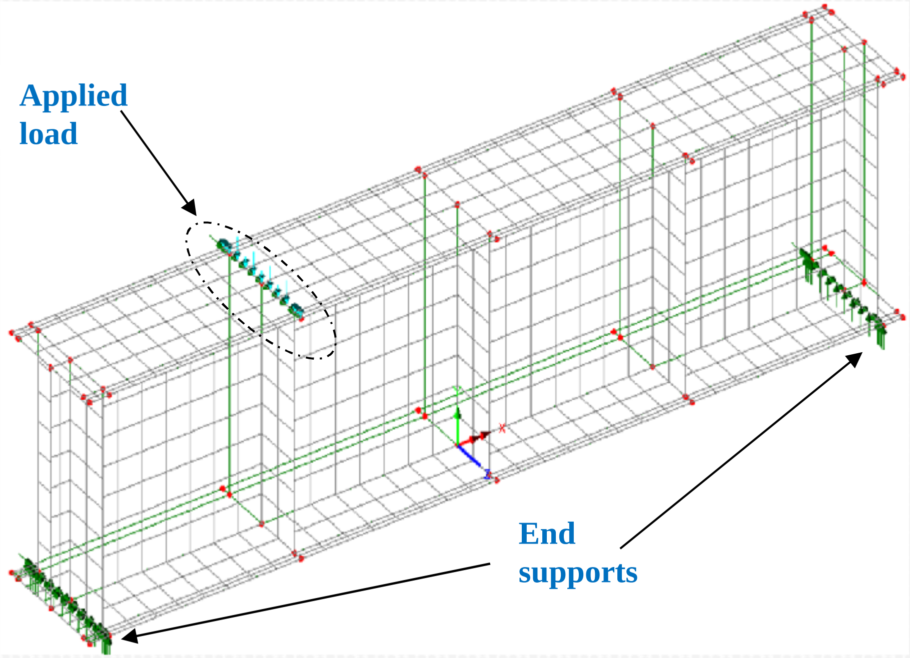
- **Imperfections**

  The deformed shape of the beam obtained from the linear eigenvalue analysis was used to account for initial geometrical imperfections

Finite element analyses (cont'd)

- **Loading and boundary conditions**

  Loading and boundary conditions used in FE analyses were applied as shown in figure



- **Analyses performed**

  a) **Linear elastic analyses**
  b) **Linear eigenvalue analyses**
  c) **Nonlinear analyses**

FEA results

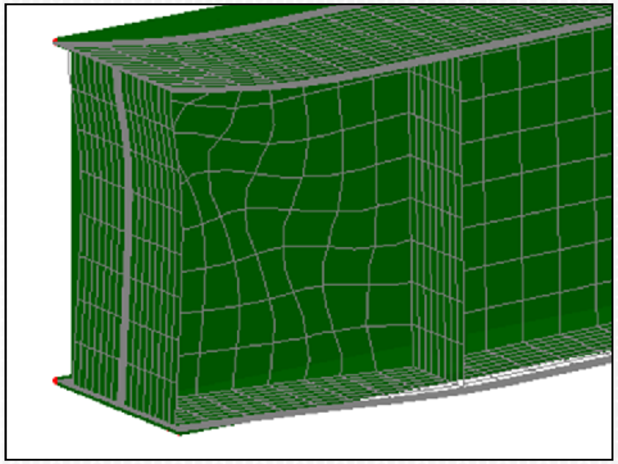
Ultimate loads and location of plastic hinges

FE model No.	Ultimate load (kN)	Ratio of ult. load of strengthened to control model	Distance of plastic hinge from top corner of end web panel (mm)	
			Top flange (A)	End stiffener (B)
Group 1: Un-strengthened control specimens				
B1	235	---	250	190
B9	295	---	250	200
Group 2: GFRP pultruded section strengthened specimens				
B2	287	1.22	250	220
B5	368	1.25	250	250
B6	430	1.46	250	250
B8	271	0.92	250	200
Group 3: FRP fabric strengthened specimens				
B3	627	2.66	250	300
B4	653	2.78	250	300
B7	489	1.66	250	280

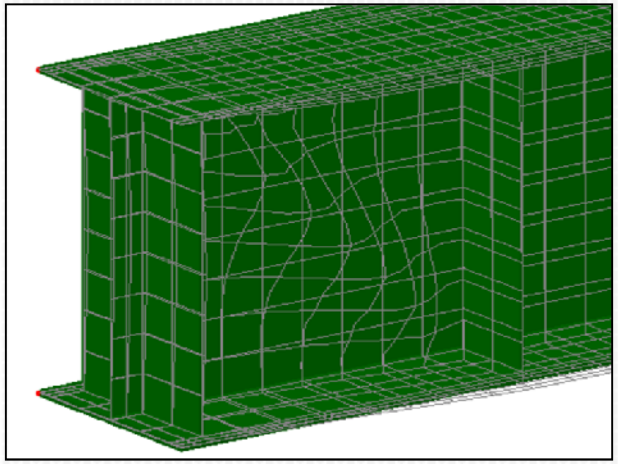
Tests and FE failure modes of specimens

Group G1: Un-strengthened control specimens

Control specimen B1



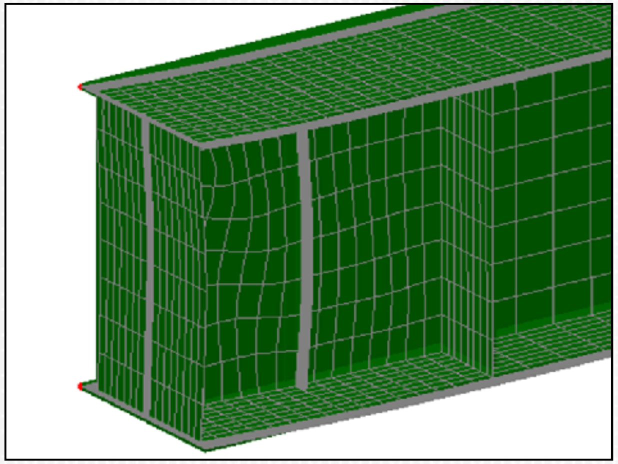
Control specimen B9



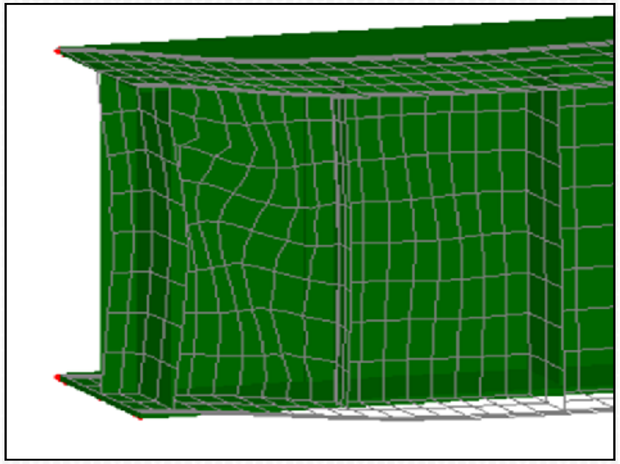
Tests and FE failure modes of specimens

Group G2: GFRP pultruded section strengthened specimens

GFRP-strengthened specimen B2



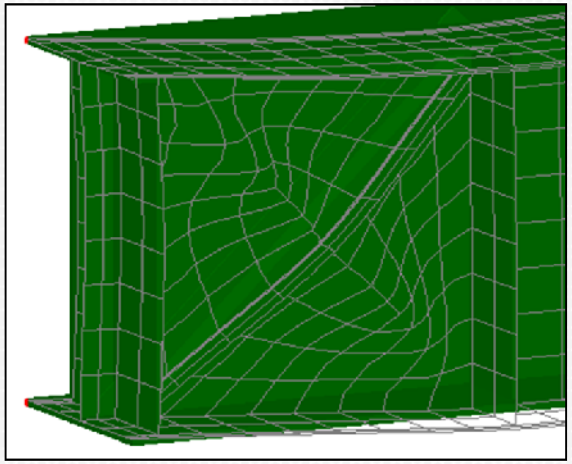
GFRP-strengthened specimen B5



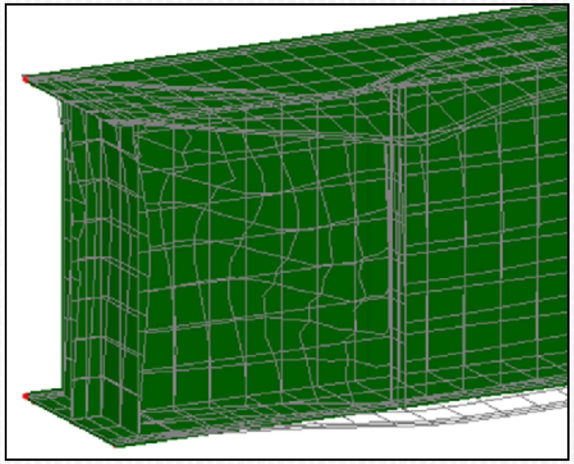
Tests and FE failure modes of specimens

Group G2: GFRP pultruded section strengthened specimens

GFRP-strengthened specimen B6

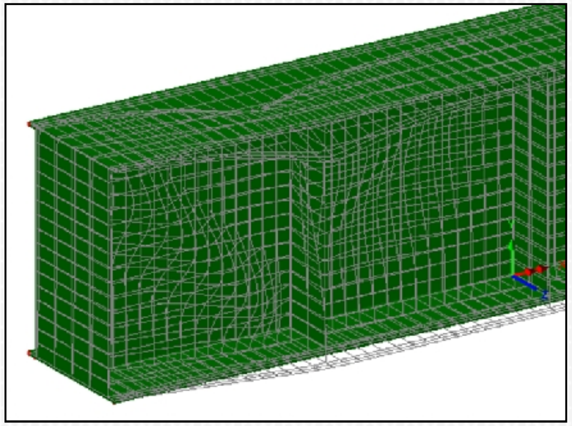
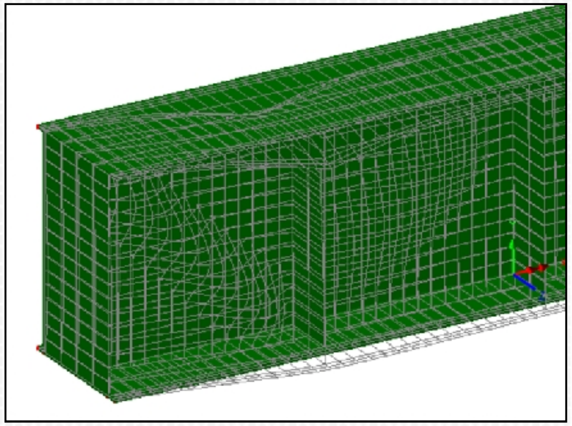
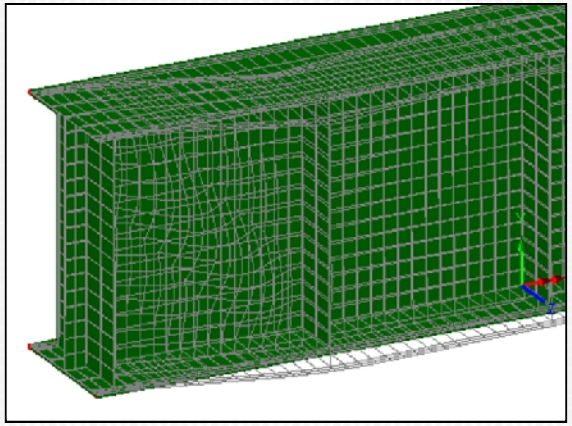


GFRP-strengthened specimen B8



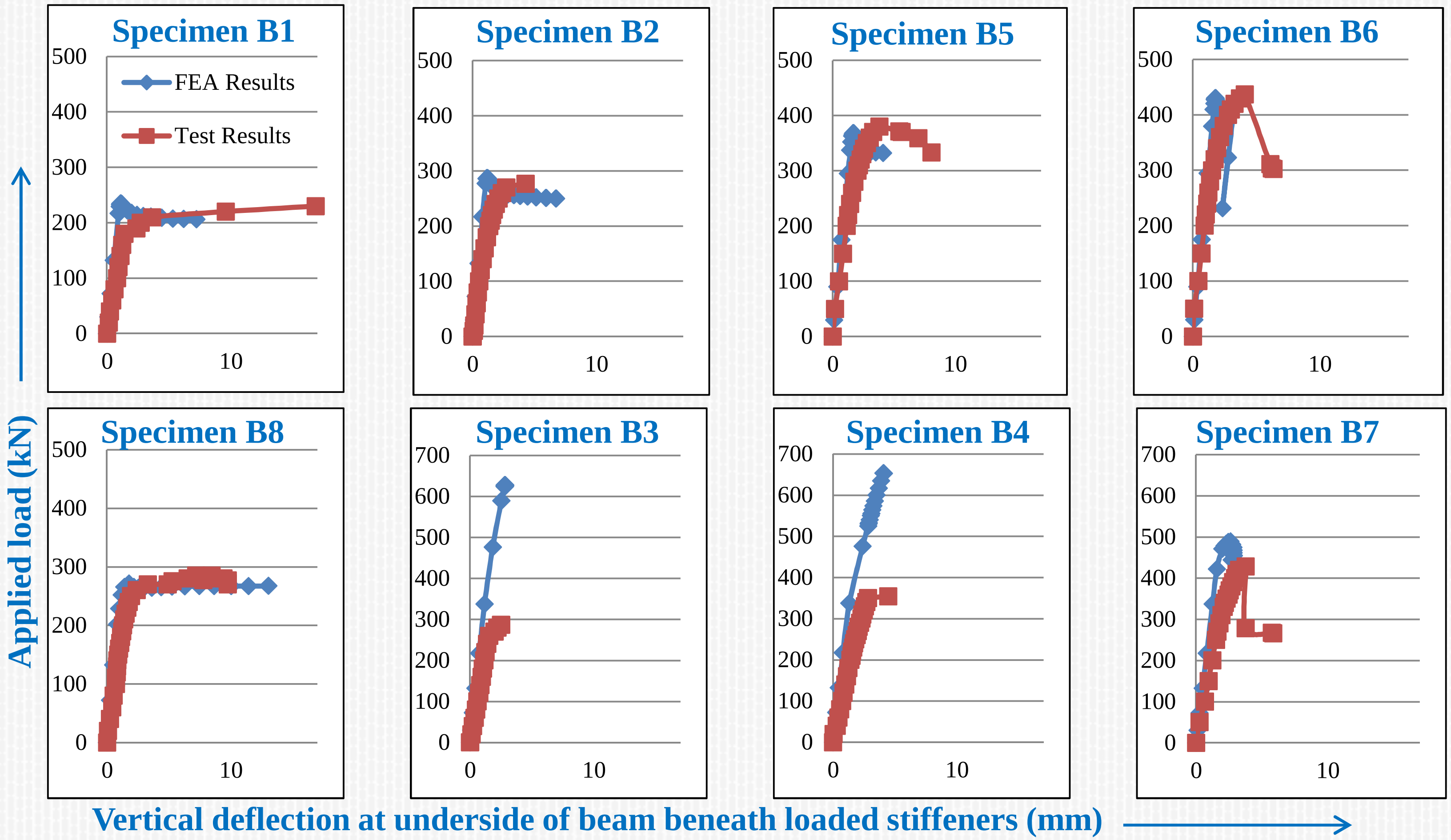
Tests and FE failure modes of specimens

Group G3: FRP fabric strengthened specimens

Carbon fabric strengthened B3	Glass fabric strengthened B4	Glass fabric strengthened B7
		
		

Comparison of test and FEA results

Applied load vs. vertical deflection plots



Note: The test and the FEA plots of specimens B3, B4 and B7 are not in good agreement because the FE analyses could not detect a bond breakdown of the steel-fabric bond that occurred in the tests

Comparison of test and FEA results (cont'd)

Ultimate loads of specimens

Specimen / model No.	Ultimate load (kN)		Ratio of ult. load of FRP-str. to control		Ratio of FEA to test ultimate Load
	FEA	Test	FEA	Test	
Group 1: Un-strengthened control specimens					
B1	235	230	---	---	1.02
B9	295	---	---	---	---
Group 2: GFRP pultruded section strengthened specimens					
B2	287	277	1.22	1.20	1.03
B5	368	380	1.25	1.29	0.97
B6	430	437	1.46	1.48	0.98
B8	271	285	0.92	0.97	0.95
Group 3: FRP fabric strengthened specimens					
B3	627	287	2.66	1.25	2.18
B4	653	354	2.78	1.54	1.84
B7	489	428	1.66	1.45	1.14

Comparison of test and FEA results (cont'd)

Location of plastic hinges and mode of specimen failure

Group No.	Specimen/ Model No.	Distance of plastic hinge from top corner of end web panel (mm)				Mode of failure in tests
		Top flange		End stiffener		
		FEA	Test	FEA	Test	
G1	B1	250	250	190	180	Out-of-plane diagonal buckling of end web panel and plastic hinges in top flange and external steel stiffeners
	B9	250	---	200	---	Out-of-plane diagonal buckling of end web panel and plastic hinges in top flange and external steel stiffeners
G2	B2	250	250	220	240	Two small out-of-plane diagonal buckles in steel web on both sides of GFRP stiffeners and plastic hinges
	B5	250	260	250	240	Two out-of-plane diagonal buckles in steel web on both sides of the GFRP stiffener, delamination of GFRP and plastic hinges
	B6	250	260	250	240	Out-of-plane diagonal buckle in steel web similar to that of B1, delamination of GFRP stiffener and plastic hinges
	B8	250	260	200	240	Out-of-plane diagonal buckling of web panel, delamination of GFRP stiffener and plastic hinges
G3	B3	250	250	300	280	Break down of carbon-steel bond, small out-of-plane diagonal buckling of web on steel side and plastic hinges
	B4	250	250	300	280	Break down of glass-steel bond, small out-of-plane diagonal buckling of web on steel side and plastic hinges
	B7	250	260	280	240	Break down of glass-steel bond, out-of-plane diagonal buckling of web on steel side and plastic hinges

Discussion of test and FEA results

- The test ultimate loads of three GFRP pultruded section strengthened specimens, B2, B5 and B6, in group G2 were increased by approximately 1.20, 1.29 and 1.48 times respectively, compared to those of the un-strengthened control specimens in group G1

- The test ultimate loads of FRP fabric strengthened specimens, B3, B4 and B7, in group G3 were increased by approximately 1.25, 1.54 and 1.45 respectively, compared to those of the un-strengthened control specimens in group G1

- The GFRP stiffeners beneath the applied load in the specimen B8 strengthened the web in a similar way to the steel stiffeners; ultimate load, 285 kN, was 0.97 times that, 295 kN, of the control FE model B9 with the steel stiffeners

- The test and FEA results for the ultimate loads, modes of failure, location of the plastic hinges and load-deflection plots for the specimens B1, B2, B5, B6 and B8 in groups G1 and G2 were in good agreement

Discussion of test and FEA results

- The test and FEA mode of failure and load-vertical deflection plots of the specimens B3, B4 and B7 in group G3 were in agreement up to breaking of bond between steel and the fabric. The FE analyses could not detect breakdown of the fabric-steel bond in B3, B4 and B7 that occurred in the tests

- The locations at which plastic hinges developed in the top flange and the external steel stiffener of all the specimens in the tests and the FE analyses were in agreement

- Proper preparation of the steel surface, tapering the ends of GFRP pultruded section stiffeners and clamping of the GFRP stiffeners as well as fabric layers helped in obtaining good steel-FRP bond

Conclusions

- With GFRP pultruded section strengthening, the ultimate loads of the strengthened specimens were increased by 1.20 to 1.48 times those of the un-strengthened specimens

- With FRP fabric strengthening, the ultimate loads of the strengthened specimens were increased by 1.25 to 1.54 times those of the un-strengthened specimens

- The test and FEA results of the ultimate loads, modes of failure and load-deflection plots for the un-strengthened and GFRP-strengthened specimens were in good agreement. The two results for FRP fabric-strengthened specimens were in agreement up to a break down of the steel-fabric bond

- Development of design guidance is under way

- Final PSG to be arranged for October/November

Acknowledgments

MANY THANKS to

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and project steering group

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Department for Transport representatives - Andy Bailey, Edward Bunting & Andrew Oldland

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