Seismic Retrofit of Steel Truss Bridge using CFRP Sheet

（鋼トラス橋の CFRP シートによる耐震補強）

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1. Introduction

In road bridges, there are members with an H-Shaped cross-section designed to work with tension forces. When an earthquake occurs, it is determined that local buckling will occur on those members due to compression forces. These members require reinforcement, but conventional methods like using steel plates and HTB have the following inconveniences:

- The increase in dead load affects the regular stress state of the structure and increases the reinforcement range needed.
- Drilling tends to increase the thickness of the plate.
- It is difficult to reinforce long members since it is needed to apply along the surface.
- Concerns on corrosion, deterioration, and maintenance.

A viable method for reinforcing these members is to use Carbon Fiber Reinforcement Polymer Sheets since it has material properties such as high elasticity, high strength, lightweight, and has less corrosion than steel materials. This material is also easy to apply since it is bonded to the member to repair/reinforce by an adhesive resin, so there is no need for special machinery or skills to apply it, there is no heat effect generated by welding on steel materials, and there is no damage generated by drilling. The inconveniences of conventional methods are solved.

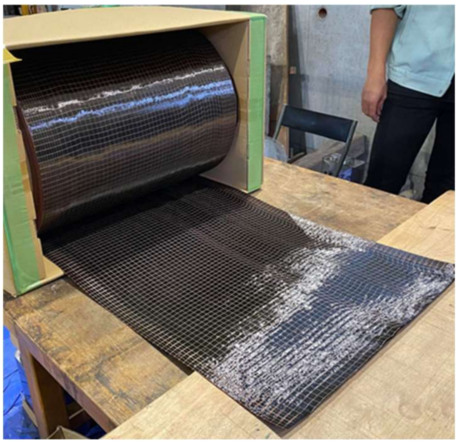


Figure 1.1 *Carbon Fiber Reinforcement Polymer Sheets*

2. Objectives

Make load-bearing capacity tests on members with an H-shaped cross-section reinforced with CFRP sheets to:

- Prove if CFRP sheet can be used as reinforcement material under a compressive load.
- Get data on the effect of Carbon Fiber Reinforcement Polymer Sheets when used as reinforcement material.
- Make the basis of the model of an H-Shaped cross-section member for future model analysis.

3. Experiment Outline

A total of 13 specimens are going to be evaluated on a load-bearing capacity test considering the member's plate thickness of flanges and web, presence or absence of reinforcement, the direction of the fibers of CFRP sheets, and the number of CFRP sheets on flanges and web. The specimens are divided into 4 cases:

- Specimen without reinforcement (b, a, c, d). to serve as comparators for the next experiments, as a way to see how the others improve.
- Specimens reinforced with CFRP sheets with fibers on vertical direction (a-1, c-1, d-1).
- Specimens reinforced with CFRP sheets with fibers in vertical and horizontal direction (a-2, c-2, d-2).
- Specimens reinforced with CFRP sheets with fibers in vertical and horizontal direction, but horizontal ones reduced to the half (a-3, c-3, d-3).

The experiment cases are summarized in table 3.1. In the table the reduced plate thickness is marked with red for flanges and blue for the web. In the part where reinforcement method is explained, the number of stacks refers to the sheets to be laminated on one flange and one side of the web.

Table 3.1 *Specimen Parameters*

Specimen	Specimen dimensions						Reinforcement Method			
	Member length (L) (mm)	Flange		Web		Ultimate state without reinforcement	Reinforcement material	Putty	Flange (Number of stacks n_f)	Web (Number of stacks n_w)
		Plate thickness (T_f) (mm)	Width (B_f) (mm)	Plate thickness (t_w) (mm)	Width (b_w) (mm)					
a	600	6	200	6	200	Flange Local Buckling	No	-	-	-
a-1							Medium elasticity CFRP Sheet	Use	Vertical direction (12)	-
a-2									Vertical + horizontal (12 + 12)	-
a-3									Vertical + horizontal (12 + 6)	-
b	600	9	200	6	200	Total Yield	No	-	-	-
c	600	6	200	4.5	200	Flange/Web Local Buckling	No	-	-	-
c-1							Medium elasticity CFRP Sheet	Use	Vertical direction (12)	Vertical direction (3)
c-2									Vertical + horizontal (12 + 12)	Vertical + horizontal (3 + 3)
c-3									Vertical + horizontal (12 + 6)	Vertical + horizontal (3 + 2)
d	600	9	200	4.5	200	Web Local Buckling	No	-	-	-
d-1							Medium elasticity CFRP Sheet	Use	-	Vertical direction (3)
d-2									-	Vertical + horizontal (3 + 3)
d-3									-	Vertical + horizontal (3 + 2)

For obtaining the plate thickness of the specimens, the standard load-bearing capacity curve of stiffening plate was used and from it, it is considered that when R>0.7, it is contemplated that the member will buckle, and when R≤0.7 it will not.

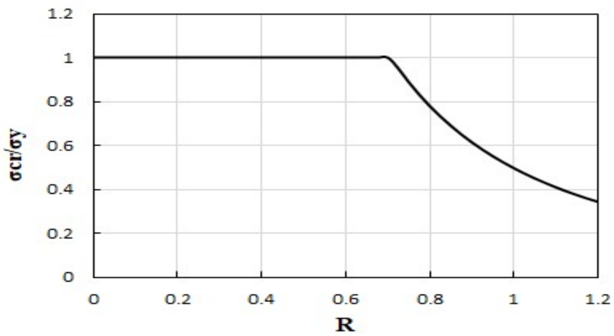


Fig. 3.1 Standard load-bearing capacity curve of stiffening plate

The different thickness of the specimens was gotten using the following formula:

$$\sigma_{cr}/\sigma_y = 1.0 \quad (R \leq 0.7)$$

$$\sigma_{cr}/\sigma_y = 0.5/R^2 \quad (R > 0.7)$$

Here

$$R = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}\cdot\frac{12(1-\mu^2)}{\pi^2 k}}$$

t: *Plate thickness* (mm)
b: *Plate width* (mm)
σ_y: *Yield load of Steel* (N/mm^2)
E: *Young's modulus* (N/mm^2)
E: *Young's modulus* (N/mm^2)
μ: *Poisson's ratio* (0.3)
k: *Buckling coefficient* (4.0 *for web*, 0.43 *for flanges*)

This equation was used in order to decide the plate thickness of both web and flanges of each experimental cases. The thickness was decided pretending to control where the local buckling will occur and having that in mind know where it is needed to reinforce with CFRP sheets.

For obtaining the number of CFRP sheets, First, a formula to get the Required reinforcement thickness for both web and flanges based on the width-thickness ratio formula mentioned before is utilized.

$$t_{sl} = \frac{b}{R'}\sqrt{\frac{\sigma_y}{E_s}\cdot\frac{12(1-\mu^2)}{\pi^2 k}} - t$$

E_s: Young's modulus(N/mm^2)
t_{sl}: Required reinforcement thickness
μ: Poisson's ratio (0.3)
b: Plate width (mm)
k: Buckling coefficient (4.0 for web, 0.43 for flanges)
R′: Width – thickness ratio after repair (0.7)
t: Plate thickness(mm)
σ_y: Yield load of Steel (N/mm^2)

The number of sheets was determined using the following formula:

$$n = \frac{t_{sl}}{t_{cf}\cdot C_n}\cdot\frac{E_s}{E_{cf}}$$

n: Number of carbon fiber sheets needed to be laminated.
t_{sl}: Required reinforcement thickness (mm)
t_{cf}: Steel equivalent thickness of carbon fiber sheet (mm)
C_n: Stress reduction coefficient (0.74)
E_s: Young modulus of Steel (N/mm^2)
E_{cf}: Elastic Modulus of CFRP Sheet (N/mm^2)

4. Specimen Reinforcement and Preparation

Before applying the CFRP sheets, the surface of the specimen is sanded with grit sandpaper and a primer is applied in the surface prepare the surface for the next things to be applied. Then, a High Elongation Elasticity Putty is applied , which purpose is to avoid CFRP sheets from peeling after buckling load and also to reduce stress transmitted to CFRP sheets. After it, an Epoxy made of Polyurea and Resin is applied as an adhesive to CFRP sheets and prevents peeling. Then CFRP sheets are applied one above the other with a layer of epoxy between them.

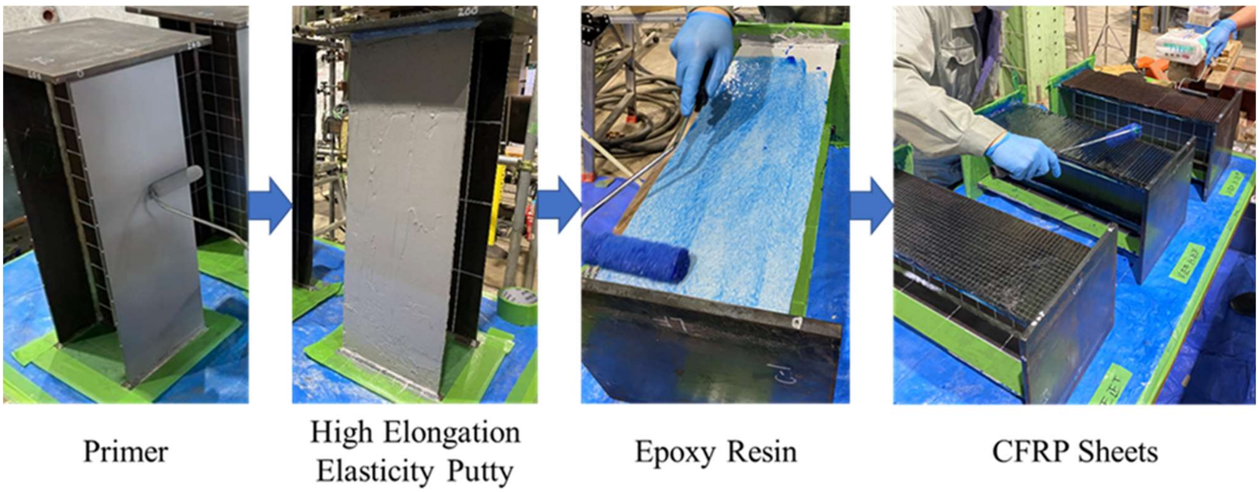


Figure 4.1 *Specimen preparation process*

In all specimen, displacement transducers and strain gauges were applied to measure vertical displacement, out-of-plane displacement, and strain during the experiments and analyze data afterwards. The location of strain displacement transducers and strain gauges is presented in the following figures:

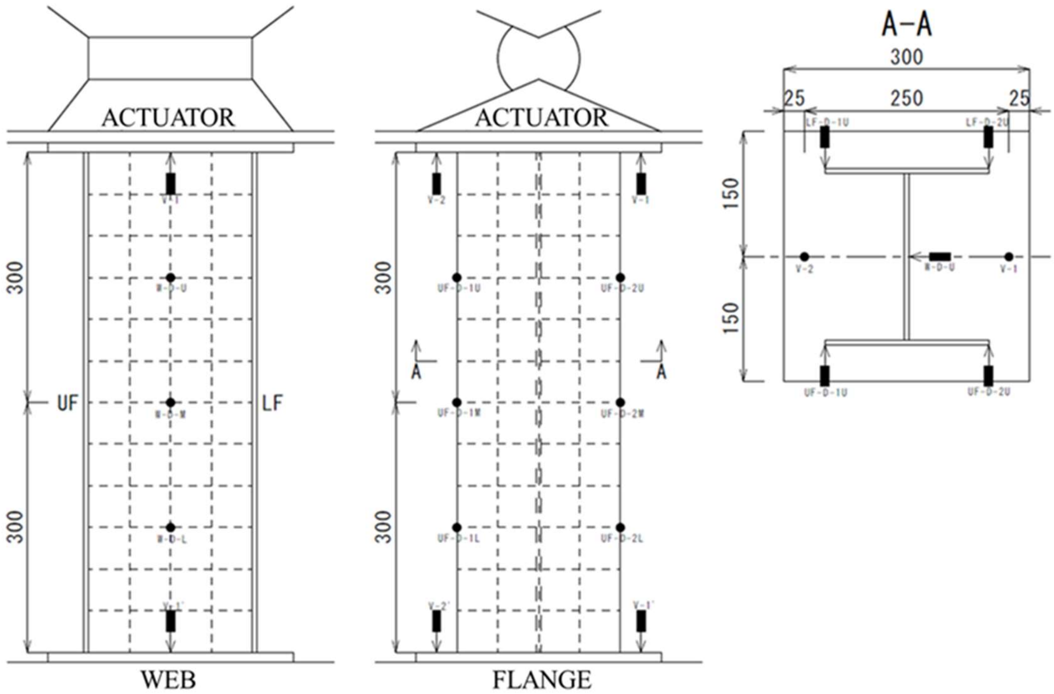


Figure 4.2 *Displacement transducers location*

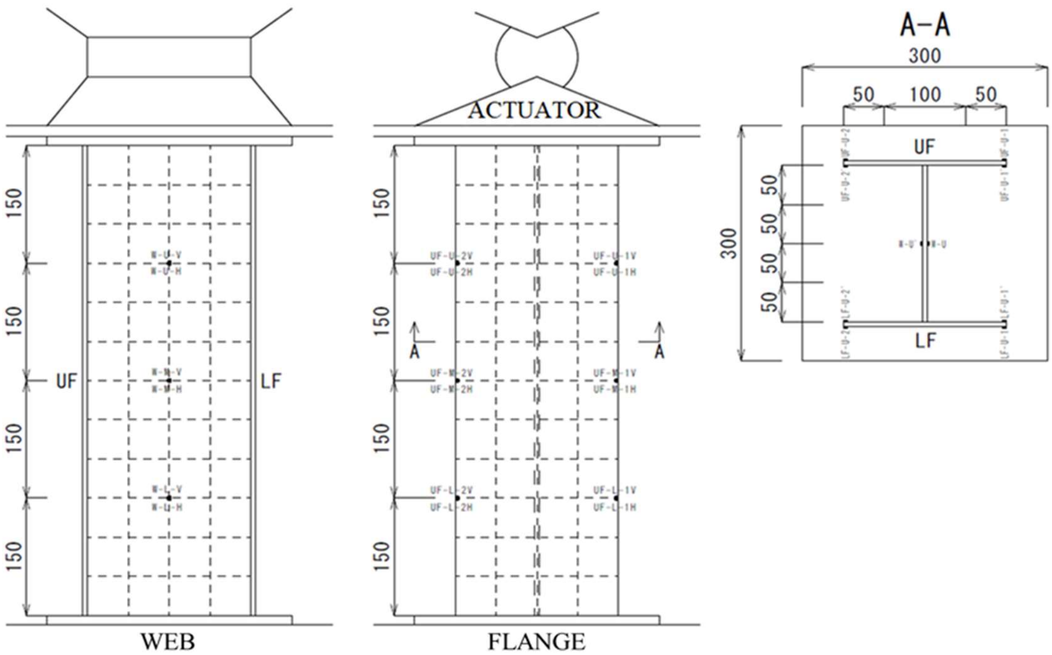
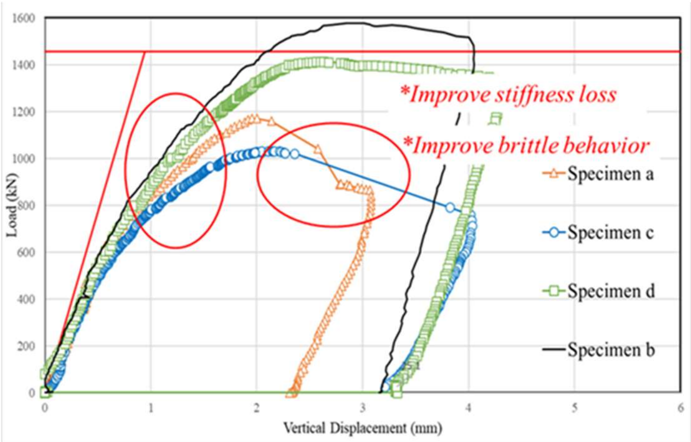


Figure 4.3 *Strain Gauges location*

5. Specimen Results

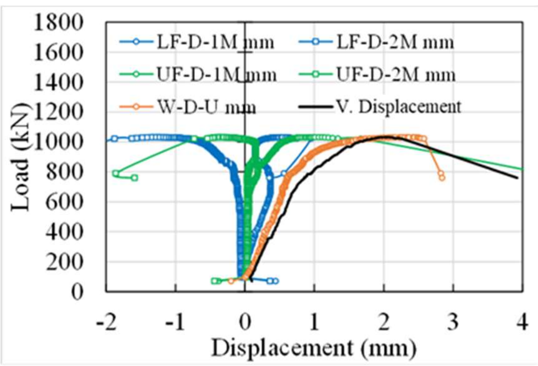
The results of the specimen with no reinforcement regarding the vertical displacement are shown in Figure 5.1. Results regarding the Maximum load are shown in table 5.1. With the results of specimen with no reinforcement, it is seen that there are two things to improve with reinforcement. It is necessary to improve the stiffness loss after web buckling and also to improve the brittle behavior presented after max load is reached.



Specimen	Maximum load Pmax^0 (kN)	Buckling Load Pcr^0	
		Web	Flange
a	1171	1062	1029
b	1577	1497	1553
c	1032	815	911
d	1413	1188	-

Figure 5.1 and Table 5.1 *Results of specimen with no reinforcement*

With the results regarding the out-of-plane displacement of specimen with no reinforcement shown in figures 5.2 and 5.3 of specimen c and d, two fracture processes are obtained. First, local buckling on the web occurs and overall stiffness decreases. After this, two scenarios are possible. In the first one, like in specimen c, flange buckling occurs and out-of-plane displacement increases, which causes a decrease in yield strength after maximum load is reached, so a brittle behavior is obtained. In the second scenario, flange yields normally, like in specimen d, and a ductile behavior is obtained afterwards.



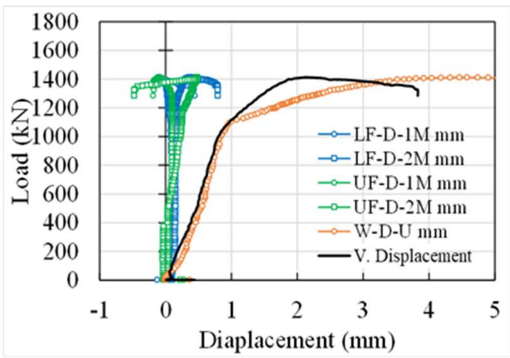


Figure 5.2 and 5.3 *Out of plane displacement of specimen c and d respectively*

The following figures show the results of series a, c, and d containing all the cases regarding the vertical displacement:

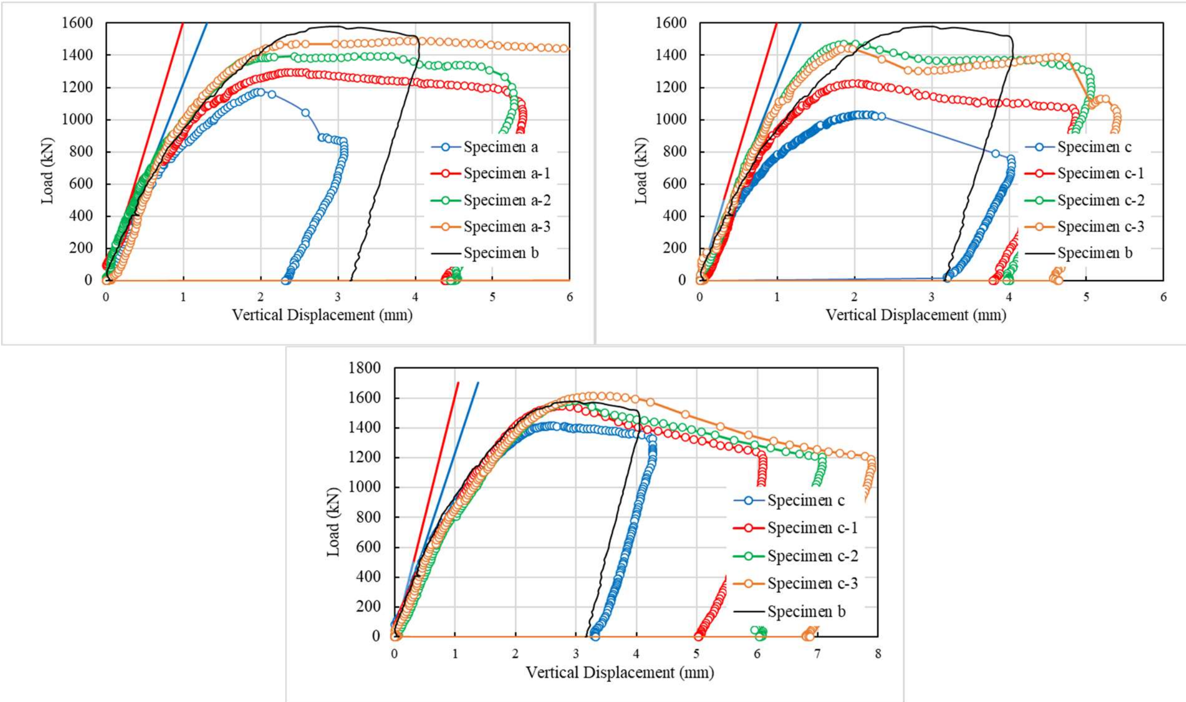


Figure 5.4, 5.5, 5.6 Vertical displacement of series a, c and d respectively

Table 5.2 Experiment Results

Specimen	Max Load	Buckling Load	
		Web	Flange
a	1171	1062	1029
a-1	1295	1006	1236
a-2	1395	1304	1295
a-3	1490	1227	1346
b	1577	1497	1553
c	1032	815	991
c-1	1224	961	1125
c-2	1472	1201	-
c-3	1443	1202	1176
d	1413	1188	-
d-1	1546	1293	1398
d-2	1581	1342	-
d-3	1615	1331	1440

What was found from the previous results is:

- CFRP sheets in vertical direction used as a reinforcement method do help to increase the buckling load and load-bearing capacity of the H-shaped cross-section member. However, overall stiffness loss after web buckling is not improved.
- Adding sheets in the horizontal direction helps to increase buckling load even more compared to case 1. It also helps increase overall load-bearing capacity.
- By reinforcing with Vertical and horizontal CFRP sheets, the overall rigidity loss due to local buckling of the web is improved.
- Reinforcing the flanges with CFRP sheets in vertical and horizontal directions helps to slow the decline in yield strength after the maximum load is reached, getting a ductile behavior.
- The buckling load of the flange increases by halving the horizontal sheet. Also, there is little change in the buckling load of the web.

6. FEM analysis of Specimen with no reinforcement

A FEM analysis of the specimen with no reinforcement (specimen b, a, c and d) is done to make the fundaments and basis for future designs related to this member and CFRP sheets reinforcements. The parameters of the models are shown in the following tables:

Table 6.1, 6.2, 6.3 Model parameters

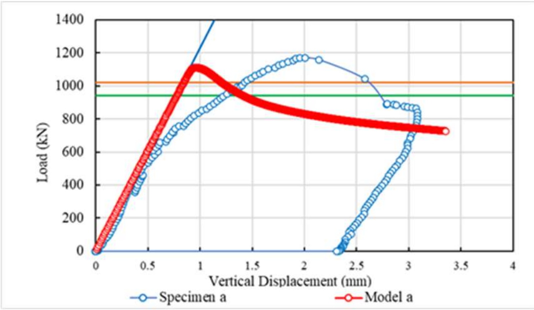
Model	Specimen dimensions (mm)				
	Member length	Flange		Web	
		Plate Thickness	Width	Plate Thickness	Width
a	600	6	200	6	200
b		9		6	
c		6		4.5	
d		9		4.5	

Material	Steel	
Elastic modulus	E=2x10^5	N/mm^2
Poisson's ratio	N=0.3	
Plasticity Model	Von Mises Plasticity	
Hardening Function	Plastic strain-yield stress	
Hardening Hypothesis	Strain Hardening	
Hardening Type	Isotropic Hardening	

Element type	Mesh Size	Load Type	Support	Analysis type
Eight-node quadrilateral isoperimetric curved shell element (CQ40S).	Element size 20 mm Hexa/Quad	Prescribed deformation to -1mm in z direction (1000 steps)	On top Fix translation in x, y, z Fix Rotation in y and z	Structural nonlinear
			On Bottom Fix translation in x, y, z Fix Rotation in x, y, z	

FEM models of the specimen with no reinforcement were done applying the effect of initial deflection according to Japan's Road Bridge Specifications. With this effect, the results of maximum load and buckling load of most of the models were in agreement with the experimental results. However, the behavior of stiffness and toughness were very different, as shown as an example in figure 6.1, showing model a and specimen a vertical displacement. The reason of this, is because in all real specimens, welding was done to assemble them. One of the effects of welding is to produce residual stresses in the assembled members. Residual stress sometimes causes a reduction in the performance of a member. Since the models of the analysis do not have the effect of welding implemented, it could be one of the reasons that there is a difference between analysis and real results. Adding the effect of residual stress could make the results closer to the real ones.

	Maximum Load (kN)			
	b	a	c	d
Model	1500	1110	976	1399
Specimen	1577	1171	1032	1413



	Buckling Load (kN)							
	b		a		c		d	
	Web	Flange	Web	Flange	Web	Flange	Web	Flange
Model	1460	1355	1023	943	726	584	1349	1215
Specimen	1497	1553	1062	1029	815	911	1188	-

Table 6.4, 6.5 and Figure 6.1 Comparison of results of the models and specimens

7. Conclusions and Future Research

Using CFRP sheets as a reinforcement material do helps to increase the load-bearing capacity of compression forces. By using, CFRP sheets in the vertical and horizontal direction, the method is more effective than by using just CFRP sheets in the vertical direction. This is because horizontal CFRP sheets help to decrease the Out-of-Plane displacement when buckling occurs, helping to get a ductile behavior. By halving CFRP sheets in the horizontal direction, there is not so much change on the web, but it improves buckling load in the flanges. Reducing the CFRP sheets in horizontal direction proves to give good results, so more experiments reducing CFRP sheets will be done in the future to get more data regarding this matter.

Future Research:

- Make experiments reducing the number of CFRP sheets in the vertical and horizontal direction to see how it affects buckling load and load-bearing capacity.
- Make experiments using CFRP sheets as reinforcement, but this time using longer members than the ones used in this case of study to see how CFRP sheets reinforcement affects them.
- Improve FEM models by adding the effect of residual stress to improve the results from the analysis so they could be more similar to the ones obtained from the experiments.
- Find a way to model CFRP sheets and make models of members reinforced with CFRP sheets to compare the analysis results with the results obtained from the experiments.