# FLEXURAL BEHAVIOR STUDY OF GFRP AND STEEL COMPOSITE I-BEAM UNDER BENDING

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The low stiffness and high deflection of glass fiber reinforced polymer (GFRP) are some of the disadvantages that prevent the full exploitation of this material in many countries. Due to these drawbacks, fifteen GFRP and steel composite I-beams were prepared for three-point bending tests. Specimens comprised of four types of beams with steel layers embedded in different locations in the flanges and web. The placing of 1.6mm or 0.8mm thickness of steel throughout the beam span in different types of I-beams is to increase the flexural stiffness of the composites. As a reference, GFRP beams without steel were also tested. The experimental results showed that 1.6mm thickness of steel layer placed in the top, bottom flanges and in the web increased the stiffness of the GFRP and steel composite beam up to 47%.

The purpose of this paper is to determine the flexural strength of GFRP and steel composite I-beams. Tests showed that this GFRP I-beam with steel has potential use for actual bridge components, especially in heavily corrosive environment.

***Key Words :*** *GFRP, steel, composite I-beam, flexural behavior, bending*

## 1. INTRODUCTION

Generally, structural degradation due to corrosion suffered by infrastructures has become a challenge in the civil engineering field. Bridges located especially in coastal environmental face rapid deterioration due to moisture, temperature and chloride attacks. In the last few decades, extensive experimental studies have been conducted in U.S and Japan on various bridge projects using fiber reinforced polymer (FRP) composite materials. These studies are made in hope to develop design guidelines, construction and maintenance standards. Many researchers have been contributing to this effort to involve in a wide variety of FRP applications to provide historical performance data in bridge constructions. This is because long-term durability of FRP composite applications is still the main concern among bridge engineers.

In Japan, FRP reinforcement was first used to replace steel bars and strengthening of structures using FRP sheets since 1997. A full scale two span continuous girder FRP footbridge was first built in 2000 located in Okinawa where corrosion decay of structure due to salt damage is the most severe in Japan[1]. The high strength to weight ratio, lightweight, corrosion resistance and ease of installation are some of the desirable characteristics where all GFRP solution was chosen for this bridge. Despite the several advantageous properties over traditional materials such as steel, GFRP profiles feature some serious disadvantages. The most important structural constraints are the low elasticity modulus, brittle behavior and high deflection which govern the design of bridges. These prevent the full application of GFRP material properties and deter the construction industry from using it.

In order to motivate the utilization of FRP composites in the industry and improve the durability of this material, a total of fifteen new GFRP composite I-beams were prepared for three-point bending tests. Specimens comprised of four types of beams with steel embedded in different locations in the flanges and web. The placing of 1.6mm or 0.8mm thickness of steel throughout the beam span in different types of I-beams is to increase the flexural stiffness of the composites. As a reference, GFRP beams without steel were also tested. According to Bank[2], composite material with anisotropic behavior exhibits a low ratio of shear-to-longitudinal elastic modulus. Due to this, shear deformation is significant during flexure. Therefore, experiment based on the Timoshenko Beam Theory to account for shear deformation was also conducted. The objective of this study is to investigate the flexural behavior of GFRP and steel composite I-beams experimentally by using Euler-Bernoulli beam theory and Timoshenko beam theory.

## 2. TIMOSHENKO BEAM THEORY

Anisotropy behavior exhibited by fiber reinforced polymer contributes a significant shear deformation that cannot be neglected in investigating flexural behavior. This is proven in Roberts, T.M. and Al-Ubaidi, H. study[3]. Further study by Kumar et al.[4] shows that GFRP profiles exhibit larger effect from shear deformation as compared to conventional steel due to lower shear modulus of resin and lower longitudinal modulus of the glass fibers. For these reasons, Timoshenko Beam Theory (TBT) is applied because it provides a more accurate approximation of the composite's flexure behavior as compared to the traditional Euler-Bernoulli Beam Theory. For a beam tested under three-point bending, the total deflection of the beam is the sum of deflection due to flexure, $v_f$ and deflection due to shear deformation, $v_s$. The mid-span displacement, $v$ is given below in Equation (1):

$$v = \frac{PL^3}{48EI} + \frac{PL}{4GK_sA} \tag{1}$$

Rearranging Eq.(1) gives the following relationship:

$$\frac{4Av}{PL} = \frac{1}{12E}\left(\frac{L}{r}\right)^2 + \frac{1}{GK_s} \tag{2}$$

where $P$ is the midspan vertical load; $L$ is the span between supports; $r$ is the section radius of gyration; $A$ is the cross section area; $E$ is the flexural elastic modulus; $G$ is the shear modulus; $I$ is the moment of inertia of cross section about the centroidal axis; $K_s$ is the shear coefficient applied to overcome the inability of the first order theory, Timoshenko Beam Theory, in order to account for the true shear stress distribution in the cross-section. To obtain $E$ and $G$ from Equation (2), three-point bending tests were performed by varying the span length. By plotting graphs of $4Av/PL$ against $(L/r)^2$ and fit a straight line to it, the gradient and intercept can be found. Values from the gradient and intercept of the straight line were then substituted into Equation (3) and Equation (4) to determine the flexural modulus and shear modulus respectively.

$$E = \frac{1}{12 \times Gradient} \tag{3}$$

$$G = \frac{1}{K_s \times Intercept} \tag{4}$$

## 3. BENDING TESTS ON GFRP AND STEEL COMPOSITE I-BEAMS

### (1) Properties of Beams

Four different types of GFRP I-beams were produced in which steel are placed in various locations in the flange or web of the beams. Each I-beam consists of two C-channel GFRPs bonded with epoxy resin in the center. Fig.1 shows an example of the composition layer of the beams. As a reference, GFRP beams without steel were also tested. A total of 15 GFRP I-beams, where three beams for each of the four different GFRP types and three steel beams with approximate equal geometry were tested under three point bending test to determine the flexural strength and deflection. Properties of the beams are listed in Table 1. Also known as punching metal (PM), the steel in the

GFRP and steel composite I beams consist of two different shapes and are shown in Fig.2

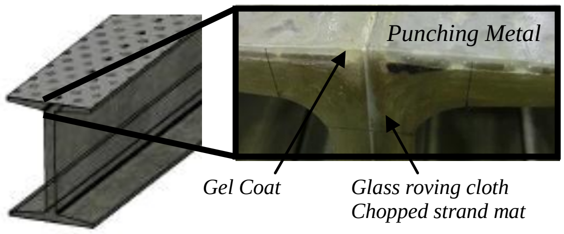



**Fig.1** Layer composition example

**Table 1** Properties of GFRP and steel beams

| Type | Material | Dimension | Length |
|---|---|---|---|
| A | GFRP | I-250*180*18*14 | 2400 |
| B | GFRP+PM | I-250*180*18*14 | |
| C | GFRP+PM | I-250*180*18*14 | |
| D | SS400 | I-250*180*18*14 | |
| E | GFRP+PM | I-250*180*18*14 | |
| F | GFRP+PM | I-250*180*18*14 | |

| Steel shape (PM) | Steel thickness (mm) | | | Qty |
|---|---|---|---|---|
| | Top Flange | Bottom Flange | Web | |
| - | - | - | - | 3 |
| Cross&Round | 1.6 | 1.6 | - | |
| Cross&Round | 1.6 | 4.8(1.6*3) | - | |
| - | - | - | - | |
| Cross&Round | 1.6 | 1.6 | 1.6 | |
| Oblong | 0.8*2 | 0.8*2 | - | |

**Fig.2** Punching metal shapes: (i) cross and round (Left); (ii) oblong (Right)

### (2) Experimental Procedure Based on Euler-Bernoulli Beam Theory

All GFRP beams consist of two C channels joined to form an I-beam. These beams were manufactured through hand lay-up process. The beams were simply supported and tested until failure in three-point bending at a span of 2000mm. Web stiffeners were placed in the web to prevent local failure or warping at supports and loading point. Strain gauges were placed near mid-span loading points to measure the strain distributions in the beam. Fig. 3 shows the three-point bending experiment setup.

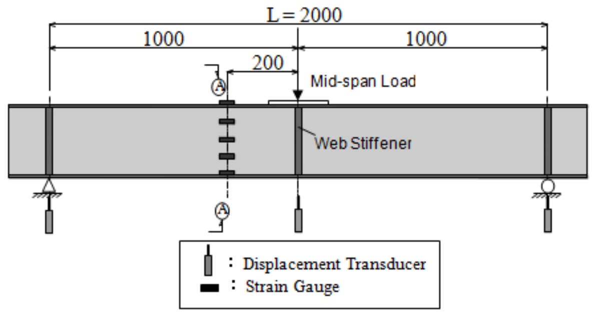
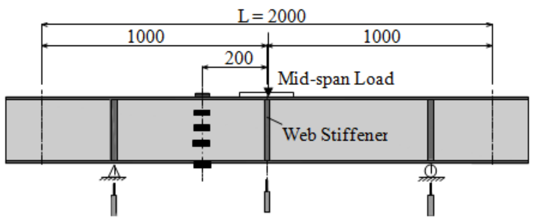


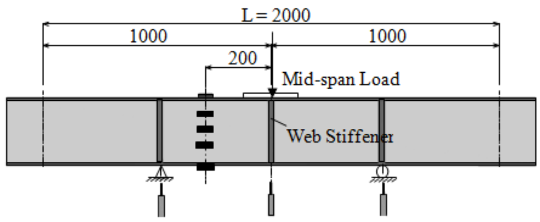

**Fig.3** Test Setup and Instrumentations

### (3) Experimental Procedure Based on Timoshenko Beam Theory (TBT)

Bank[2)] proposed a multi-span bending test procedure for determining $E$ and $G$ simultaneously through three-point bending test and the plotting of graphs of $4Av/PL$ versus $(L/r)^2$. Beams tested based on TBT consist only the second and third specimen of each different beam types. By varying the span having values of $(L/r)^2$ equals to 100, 200, 300 and 400, bending tests were carried out on each span. Example of test on a beam by varying span length is shown in Fig.4.




$(L/r)^2$=400




$(L/r)^2$=100

**Fig.4** Bending test on beams with varying spans

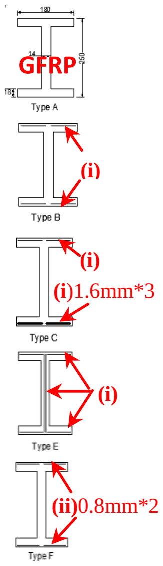
## 4. EXPERIMENTAL RESULTS

### (1) Results based on Euler-Bernoulli Beam Theory

The results of all the beams tested indicating the maximum load and corresponding deflection were listed in Table 2. The elastic modulus, $E$ was calculated using only the deflection due to flexure, $v_f$ in Equation (1). Fig.5 shows the load deflection curves for all beams.

**Table 2** Experimental results and flexural stiffness, *E*

| Beam | *E* (GPa) | Average | % |
|---|---|---|---|
| A1 | 13.12 | | |
| A2 | 17.07 | 14.74 | - |
| A3 | 14.02 | | |
| B1 | 20.40 | | |
| B2 | 18.68 | 19.07 | +29 |
| B3 | 18.14 | | |
| C1 | 20.74 | | |
| C2 | 21.75 | 21.27 | +44 |
| C3 | 21.32 | | |
| E1 | 20.12 | | |
| E2 | 22.91 | 21.65 | +47 |
| E3 | 21.92 | | |
| F1 | 21.25 | | |
| F2 | 20.73 | 20.86 | +42 |
| F3 | 20.60 | | |




*%: Percentage Difference

It is observed that beam type E yielded the highest flexural modulus of 21.65GPa as compared to the all GFRP beam type A of only 14.74GPa. To sum up, all composite beams with steel layers either in the flanges, web, or in both locations show an increase in the flexural stiffness. Composite beams especially type C, E and F have more layers of steel placed in their respective flanges and web locations prove to be a stiffer material comparing to the other specimens.

Hence, it can be concluded that the flexural modulus depends on not only the GFRP and steel composition but also the position of each material layer of the composite. By placing stiffer layers away from the neutral axis, the flexural modulus is increased significantly. In addition, the steel layer located at tension side of the beam can enhance the tensile properties and make sure that the beam will fail in a compression mode, which is more ductile.

The use of steel in the GFRP composite layer as a flexural strengthening material proved to be suitable and show potential use of it in actual bridge component.

## (2) Results based on Timoshenko Beam Theory

For example, two values of load in Fig.6 and its corresponding deflection were chosen from the linear load-deflection range to be used to plot a straight line as shown in Fig.7. The same procedure was followed on all the spans having values of (*L/r*)2=100 to 400. The graph of *4Av/PL* versus $(L/r)^2$ was drawn where a linear regression of the two beams' data was then

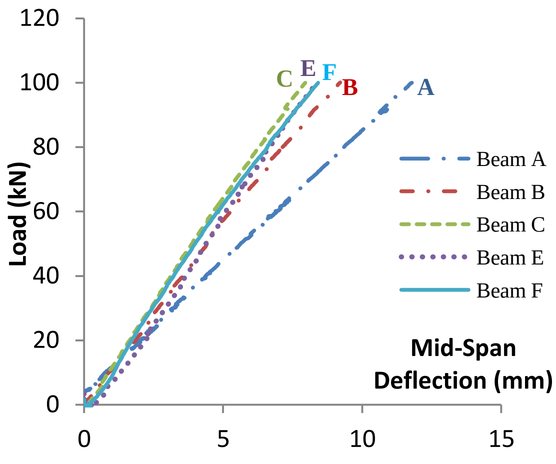



**Fig.5** Load deflection curves for all beams

performed to obtain its linear and angular coefficient. These values of the gradient and intercept were substituted into Equation (3) and Equation (4) to determine the flexural and shear moduli of the specimens simultaneously.

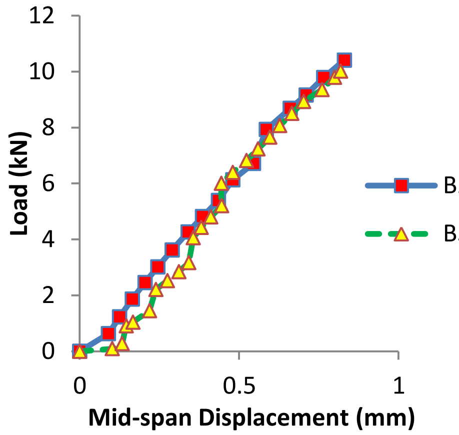
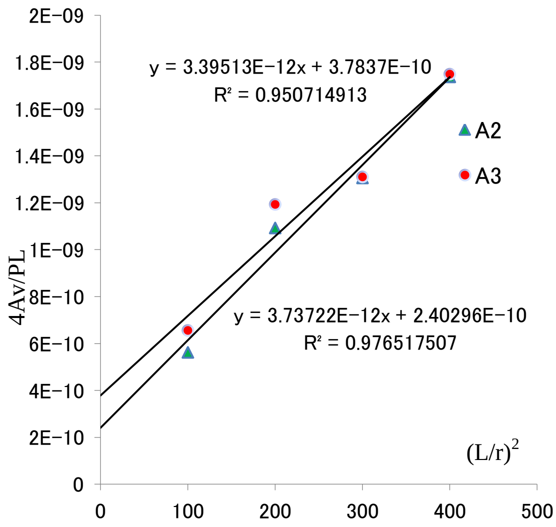



**Fig.6** Load Displacement Curve of Beam B2 and B3on span $(L/r)^2$=400



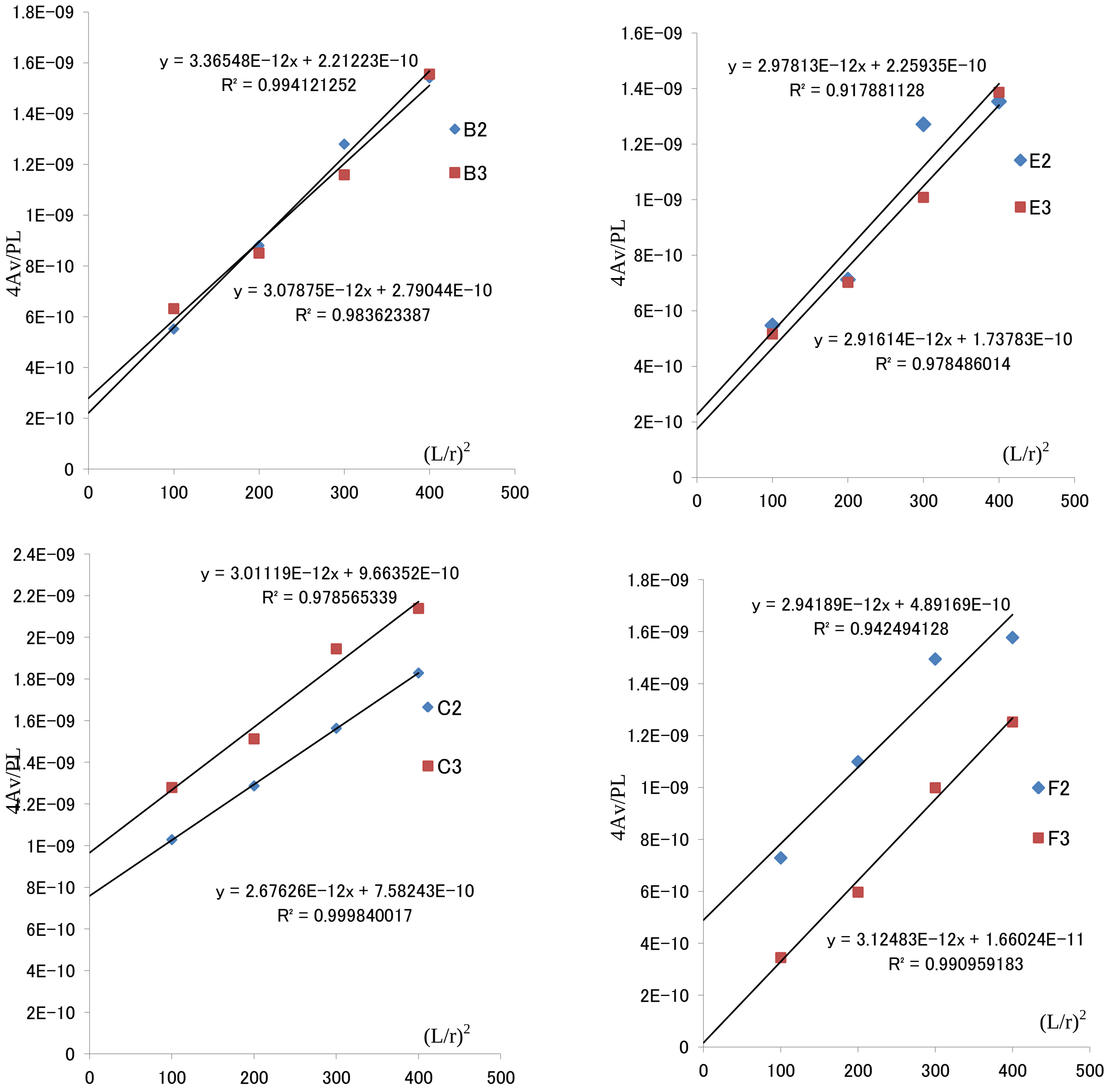



**Fig.7** Plots using Equation (2) to obtain section moduli *E* and *G* simultaneously

It was observed from these plots that the flexural rigidity strongly dependent on the linear fit of all data points obtained from the multi-span bending test. A slight change in the gradient of the straight line from the plot could produce different values of the flexural rigidity because this multi-span procedure is very sensitive.

Study by Bank[2)] and Mottram[5)] stated that a repeat of the tests twice or more is sufficient to obtain the best straight line in the plots. Theoretically, only two different spans are required to plot two points for the establishment of the best fit straight line. In order to ensure small errors in the plots, four different spans of tests were conducted and the straight line gradients were obtained through a linear regression approach.

Fig.7 also shows the linear regression of all the plots from the lowest accuracy of 0.92 to a high 0.99. The more closer of these values to 1.0 indicating the more accuracy and positive linear relation between the terms in Equation (2).

However, it is suggested here that more spans should be carried out in the experiment. Starting with 50 with an increment of 50 from $(L/r)^2$=50 to 500 will show more data points for more accurate plot.

## 5. RESULTS COMPARISON

Table 3 shows the comparison of flexural modulus, *E* for all GFRP composite beams between the results obtained by experiments based on Euler-Bernoulli beam theory (E.-B.Th.) and Timoshenko Theory (Timo.Th.) respectively. It can be noted that the stiffness of the beams determined by Timoshenko Theory are higher than the results obtained by Euler-Bernoulli beam theory.

This state can be explained from Equation (5) and Equation (6) which were rewritten from Equation (1) as shown below. $E_A$ is the apparent flexural modulus which can be defined as a beam's resistance towards deflection due to only bending, neglecting deflection due to shear deformation. Equation (6) shows that the apparent flexural modulus, $E_A$ is always lower than the true flexural modulus, $E$. In addition, the multi-span experiment conducted based on Timoshenko Theory produced the largest possible flexural stiffness value combined with eliminated shear effect. These reasons are in good agreement with the results obtained in Table 3.

**Table 3** Comparison of flexural modulus, *E* (GPa) between Euler-Bernoulli and Timoshenko beam experiments

| Beam | E.-B. Th. | Timo. Th. | | |
|---|---|---|---|---|
| | | Specimen2 | Specimen3 | Average |
| A | 14.74 | 22.30 | 24.54 | 23.42 |
| B | 19.07 | 24.80 | 27.10 | 25.95 |
| C | 21.27 | 27.67 | 27.12 | 27.40 |
| E | 21.65 | 28.00 | 28.60 | 28.30 |
| F | 20.86 | 28.30 | 26.70 | 27.50 |

$$\upsilon = \frac{PL^3}{48EI}\left[1+\frac{12E}{(L/r)^2 GK}\right] \qquad (1)$$

$$E = \frac{PL^3}{48\upsilon I}\left[1+12\frac{E/GK}{\left(L/r\right)^2}\right]$$

$$\frac{1}{E_A} = \frac{1}{E}\left[1+12\frac{E/GK}{\left(L/r\right)^2}\right] \qquad (2)$$

## 6. CONCLUSION

The flexural modulus of the GFRP and steel composite beams was evaluated experimentally by Euler-Bernoulli beam theory and Timoshenko beam theory. Considering only the elementary Euler-Bernoulli beam theory, it was observed from the load displacement curve of beams tested until failure that the beams behave in a linear elastic behavior. Due to the reason of the anisotropic behavior in composite materials that increases the shear deformation in the beam, a multi-span experiment approach based on Timoshenko beam theory was also conducted to take shear effect into consideration.

The results obtained were compared and it was confirmed that the effect of shear deformation on the bending tests cannot be neglected. Beam type E is the beam with largest flexural modulus compared to other specimens. By placing steel layers of 1.6mm embedded in the top and bottom flange, and also in the web, the load bearing capacity was increased up to 47%.

Overall, all composite beams with steel layers either in the flanges, web, or in both locations show an increase in the flexural stiffness. GFRP and steel composite beams such as type C, E and F have more layers of steel placed in their respective flanges and web locations prove to be a stiffer material comparing to the reference beam type A.

It can be concluded that the flexural modulus depends on not only the GFRP and steel composition but also the position of each material layer of the composite. Placing stiffer layers away from the neutral axis, increase the flexural modulus of the material significantly. Finite element modeling and analysis of all the GFRP and steel composite beams under bending test will be conducted in the near future to verify the experiment results with the numerical analysis.

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## APPENDIX 1: LOAD DISPLACEMENT CURVES

The following Fig. A1 to Fig. A4 show results of load displacement curve of beams A, C, E and F from span $(L/r)^2=400$. Two values of loads and its corresponding displacements were chosen from the linear load-deflection range to be used to plot the graphs as depicted in Fig.7.

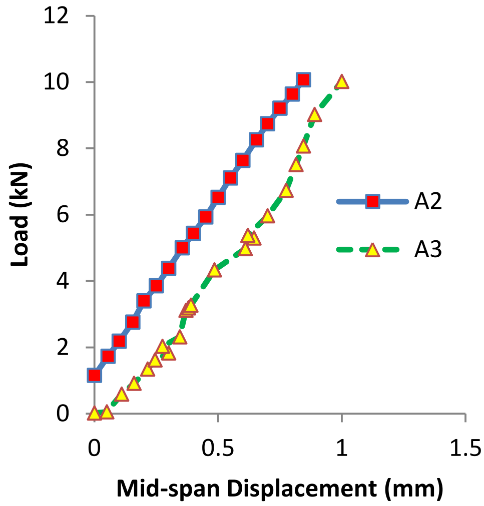



**Fig.A1** Load displacement curve of beam A2 and A3 on span $(L/r)^2$=400

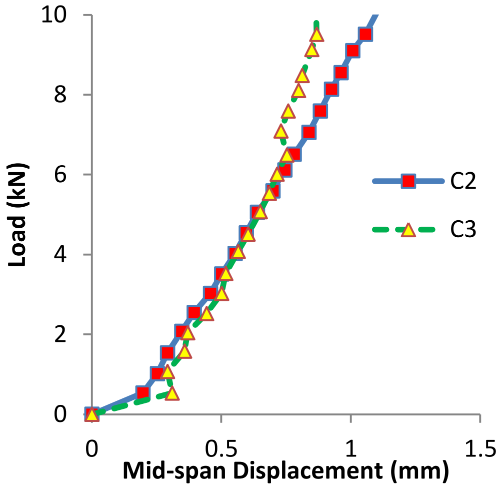
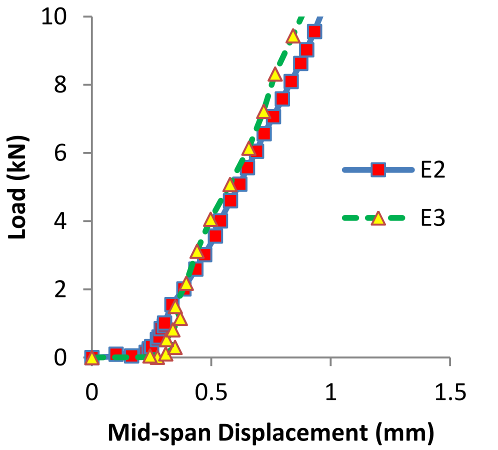



**Fig.A2** Load displacement curve of beam C2 and C3 on span $(L/r)^2$=400




$(L/r)^2$

**Fig.A3** Load displacement curve of beam E2 and E3 on span $(L/r)^2$=400

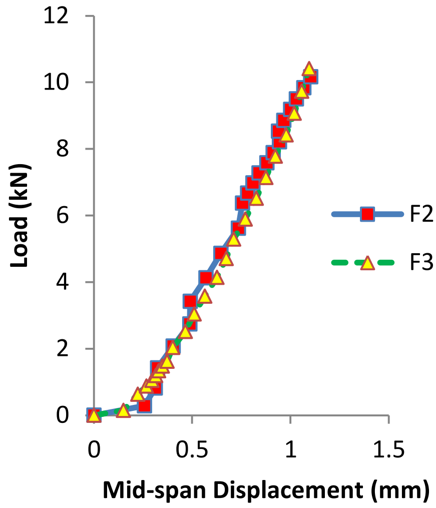



**Fig.A4** Load displacement curve of beam F2 and F3 on span $(L/r)^2$=400

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