

Experimental and Analytical Evaluation of Reinforced Concrete Beams Strengthened Using a Near-Surface Mounted CFRP U-Wrap Technique

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Article

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Abstract

This paper presents experimental and theoretical investigation of flexural behavior of RC beam specimens strengthened using the NSM technique, where NSM was implemented by CFRP U-wrap. A total of 16 beams with dimensions $100 \times 200 \times 1500$ mm were fabricated and subjected to four-point bending test. Comparison of unstrengthened control specimens with specimens strengthened using CFRP sheets embedded in a surface-mounted groove using two-component epoxy resin [1] is carried out.

The experimental testing was intended to determine important parameters as load-deflection behavior, maximum load, stiffness, ductility, and cracking patterns. The reinforced beams have proved to have significantly better performance compared to the control beams with respect to the load carrying capacity and deflection properties, thus revealing the effectiveness of the used reinforcement technique. It has also been determined that the use of the U-wrap composite laminate results in a notable increase in the lateral confining action and improvement of the CFRP-concrete bond.

Besides the experiments, the finite element analysis has been performed using a computer simulation tool in order to analyze the structural response of the beams. It has been found out that there is an excellent correlation between the experimental and the simulated data with respect to the load-deflection behavior and failure modes. Thus, the current study reveals that the Near-Surface Mounted CFRP U-wrap technology is a potential tool to improve the flexural performance of RC beams and hence may be considered a feasible reinforcement/restoration method [2].

1 Introduction

Reinforced concrete (RC) is one of the most popular materials used in the construction of buildings owing to the characteristic of being durable. However, in most cases, there is need for strengthening of structural members due to loading increase, aging of members, and environmental effects. There has been development of smart retrofitting technology where improvement in structural performance is done without making much change to the existing structure. Fiber reinforced polymer (FRP) composites including carbon fiber reinforced polymers (CFRP) are widely accepted due to the high strength to weight ratio, resistance to corrosion, and less labor intensity involved [3].

Moreover, CFRP materials are widely used for strengthening flexural properties of RC beams. Of the various available techniques, the Near Surface Mounted (NSM) technique has been found to be very promising as it increases the level of bonding of the reinforcement and also provides greater protection to the strengthening materials unlike conventional externally bonded techniques. Grooves are provided on the concrete surface and the CFRP materials are bonded using epoxy resin in NSM technique, thereby increasing the bond strength of the structure [4]. Besides this, the effectiveness of this system can also be enhanced through the implementation of U-wrap configuration because of confinement and interaction between CFRP and concrete.

In the current research, the flexural behavior of reinforced concrete beam strengthened through near-surface mounted CFRP U-wrap system has been investigated. The testing was performed on $100 \times 200 \times 1500$ mm size specimens and their performance was compared with that of control beams. Load deflection behavior, ultimate load carrying capacity, stiffness, ductility and crack pattern were selected as the critical parameters. In addition to the experiments, an analytical study in terms of finite element modeling has been carried out to support the experimental investigation. The objective of the present study is to assess the performance of the strengthening technique as well as its applicability in real structure.

2 Literature Review

The use of FRP composites for reinforcing the reinforced concrete (RC) beams has been studied widely, and CFRP has become one of the top reinforcing materials. The pioneering work of four authors [3]. 3.1 CFRP reinforcing system J. G. Teng, J. F. Chen, S. T. Smith, and L. Lam revealed that effectiveness of CFRP reinforcement highly depends on the behavior of the bond between CFRP and concrete substrate. In order to address the weaknesses of the externally bonded method, the Near Surface Mounted (NSM) method has been introduced and intensively studied by L. De Lorenzis and J.G. Teng [5].

More experimental research by T. Hassan and S. Rizkalla showed that NSM RC beams strengthened with CFRP had better performance in both yield and ultimate loads and improved the performance of cracking. S.A. Rizkalla [35] said that this means that there will be an easier installation of the strengthening technique. Moreover, through the numerical studies conducted by R.A. Hawileh, H.A. Rasheed, J.A. Abdalla, and A.K. Al-Tamimi, it was proven that FEA is able to accurately predict the flexural behavior of the strengthened RC beams [6].

In recent years (2023–2026), researches were made on improving NSM systems and using them along with hybrid strengthening methods. In the recent experiments, it was shown that the capacity to bear loads as well as the rigidity and cracking strength of RC beams is increased to a large extent with the use of NSM CFRP system, and the significance of adhesive properties and groove geometry has been highlighted [7].

Studies have also been conducted on the application of U-wrap and jacketing techniques along with NSM and results indicate increased confinement, better crack behavior and ductility performance. This implies that there is a development towards strengthening systems with increased strength and serviceability. Although these techniques are major technological developments, however, only few studies could be located related to the application of CFRP strips in NSM system along with U-wrap technique for flexural strengthening. In addition, further research is required to combine experimental studies and analysis for modeling such strengthening systems. In this regard, an attempt has been made to analyze the flexural response of NSM reinforced RC beams using U-wrap technique in this study [8] [9].

3 Materials and Properties

The materials used in this study are typical of those found in traditional RC construction and advanced composite retrofit systems. The strengthened beams behaviour is influenced by the mechanics and bonding properties of the building materials (concrete, steel reinforcement, CFRP sheets, and epoxy adhesive).

3.1 Concrete

Normal Portland Cement (OPC) was employed in the formation of concrete used for the beam samples. The preparation of the mix was designed to required compressive strength for structural uses. The material of fine aggregates and coarse aggregates meet the standard. All the specimens were cast and cured in a controlled environment for 28 days to bond sufficient strength before the test.

3.2 Steel Reinforcement

High yield strength deformed (HYSD) steel bars were utilized as longitudinal reinforcement to counteract tensile stresses and mild steel stirrups were used as shear reinforcement. The reinforcement layout was such that the beams would primarily fail in bending under the load [10].

3.3 CFRP Sheet

Unidirectional CFRP sheets were employed as the strengthening media. The CFRP sheets were chosen because of their high tensile strength, low weight and corrosion resistance. They were placed in the longitudinal direction of the beam in U-wraps to increase the flexural strength and the confinement in the tensile region [11].

3.4 Epoxy Adhesive

A two-part epoxy based on Araldite LY 556 resin with Aradur HY 951 hardener was applied on bonding of the CFRP sheets to the concrete substrate. This particular epoxy system was chosen for its outstanding adhesion properties, reasonable pot-life, and for the fact that it allows effective stress transfer between CFRP and concrete. The components were combined at a ratio of 100:10–12 (resin: hardener by weight) for best results. The epoxy properties are summarized in Table 1. mechanical and physical .

Table 1
Properties of Epoxy Adhesive (Araldite LY 556 / Aradur HY 951)

Property	Resin (LY 556)	Hardener (HY 951)	Unit
Viscosity at 25°C	10,000–12,000	10–20	mPa·s
Density at 25°C	1.15–1.20	0.97–0.99	g/cm ³
Mix Viscosity	~ 1700	—	mPa·s
Gel Time at 25°C	120–180	—	minutes
Tensile Strength (laminate)	35–38	—	kg/mm ²
Flexural Strength	45–50	—	kg/mm ²
Mixing Ratio	100:10–12	—	by weight

4 Experimental Programme

The flexural behaviour of RC beams in unstrengthened and strengthened conditions, was investigated by the experimental programme. The research involved casting specimens, CFRP strengthening, and testing under controlled loading.

4.1 Specimen Details

Six reinforced concrete beams with dimensions 100 mm × 200 mm × 1500 mm were cast. All specimens were fabricated with the same concrete mixture and reinforcement details. The beams were split into two groups: the control beams (unstrengthened) and the beams strengthened with CFRP sheets. Both control and strengthened beams were tested; the former in their as-is state, the latter using a U-wrap configuration strengthening.

4.2 Strengthening Procedure

The strengthening was performed by NSM U-wrap method in CFRP. CFRP sheets of 420 mm × 1300 mm were utilized for reinforcement. To ensure accurate positioning of the CFRP sheet, grooves were cut out in the required region on the beam surface. The dust and loose particles were cleaned off from the surface before application of the adhesive.

A two-part epoxy adhesive was spread into the grooves, and the CFRP sheet was positioned and pressed down to get adequate bonding. The sheet is U-wrapped around the beam section. Subsequently, after the strengthening procedure, the reinforced area was covered with one layer of M30 grade concrete for covering the CFRP and to regain the beam cross section. The beams were allowed to cure properly before testing.

4.3 Test Setup

All the beams were subjected to the same loading conditions for a fair comparison between the control and strengthened beams.

4.3.1 Test Setup for Control Beams

The control beams were subjected to the four-point bending test using a load frame. The beams were simply supported, and a two-point load was applied incrementally. Deflections were measured using LVDT located at certain points, including the mid-span. The behavior of the beams was monitored up to rupture.

Table 2
Load deflection of Control beams

LOAD	DEFLECTION (mm)		
(kN)	LVDT1	LVDT2	LVDT3
0	0	0	0
5	0.224	0.216	0.329
10	0.446	0.438	0.754
15	0.789	0.687	0.928
20	0.936	0.824	1.072
25	1.086	0.998	1.258
30	1.716	1.308	2.358
35	2.386	2.286	2.758
40	2.781	2.528	2.974
45	2.996	2.806	3.198
50	3.261	3.123	3.479
55	3.487	3.307	3.659
60	3.659	3.458	3.895
65	3.925	3.589	4.025
68	4.285	4.095	4.521

4.3.2 Test Setup for Strengthened Beams

The strengthened beams were subjected to testing under the same loading configuration as the control beams to ensure uniformity. The load was applied stepwise, and the deflection was recorded during the

test. Particular attention was focused on the CFRP U-wrap, crack propagation, and the total load capacity. Due to the existence of CFRP and the added concrete layer, the fortified beams demonstrated different response.

Table 3
Load deflection of U-Wrap beams

LOAD	DEFLECTION (mm)		
(kN)	LVDT1	LVDT2	LVDT3
0	0	0	0
5	1.235	0.879	1.956
10	2.259	1.998	2.598
15	2.965	2.659	3.589
20	3.691	3.356	4.189
25	4.689	4.159	5.245
30	5.378	4.965	5.845
35	6.189	5.846	6.589
40	6.914	6.489	7.345
45	7.689	7.125	8.124
50	8.569	8.023	8.915
55	9.489	9.123	9.91
60	10.598	10.125	10.998
65	11.597	11.164	11.936
70	12.258	12.015	12.845
75	13.589	12.891	13.956
80	14.294	13.856	14.798
85	14.956	14.869	15.265
90	15.426	15.391	15.689
95	15.875	15.589	15.996
100	16.025	15.936	16.452
105	16.625	16.578	16.758

5 Numerical Investigation

The numerical investigation is performed by means of finite element analysis to model the response of RC beams subjected to flexure. Analytical solutions were employed to verify the experimental results and to gain a deeper insight into the behavior of the structure [12].

5.1 Finite Element Modelling

A 3D finite element model of the beam specimens was established by ANSYS workbench. The model geometry was selected according to the experimental dimensions of the beams 100 mm (b) × 200 mm (h) × 1500 mm (l). To analyse their performance under the same loads, two models were developed, one for the control and one for the strengthened beams. Concrete was modelled with solid elements and potential cracking and crushing behaviours. The steel reinforcement was modelled by embedded elements within the concrete and the CFRP sheet was modelled by shell elements. Suitable 'contact' elements were defined to represent the behaviour of the interface between the concrete, epoxy, and CFRP [13].

5.2 Material Properties

The material properties taken for the numerical model were from typical values and experimental considerations. The concrete was modeled by a nonlinear material model which can consider both tensile cracking and compressive crushing behaviors. Steel reinforcement was represented as an elastic – plastic bilinear material.

The CFRP sheet was assigned linear elastic orthotropic properties with high tensile strength and modulus in the fibre direction. The epoxy layer was assumed to provide perfect bonding between the CFRP and concrete for modelling simplicity.

5.3 Boundary Conditions and Loading

The boundary condition was specified to mimic the experimental setup [13]. The beam is simply supported at both end modeled. Two-point loading was applied symmetrically to represent the four-point bending scheme in the experimental programme. The beam was loaded in steps in order to obtain nonlinear response of the beam. The analysis was performed using an iterative solution technique at each load step to obtain convergence.

5.4 Numerical Results

The finite element models yielded load-deflection responses, stress distribution and crack patterns of both control and retrofitted beams. The magnitude of load capacity predicted by these numerical results for the retrofitted beams is greater than that of the control ones. The predicted ultimate load values obtained by the numerical model were in good agreement with the experimental load values with a small difference. The enhanced beam model also exhibited higher deformation capacity and crack propagation were further retarded, in good agreement with the experimental results.

5.5 Validation of Numerical Model

The numerical model was validated by a comparison between the load– deflection curves obtained from the finite element analyses and the experimental ones. The two showed a good agreement especially in elastic and post cracking regions. Small differences in the post-yield region can be attributed to modeling assumptions simplifications like perfect bonding, homogeneity of materials. Nevertheless, the general agreement indicates that the finite element analysis can be used to successfully predict the behavior of RC beams strengthened with CFRP .

6 Results and Discussion

The performance of the control and CFRP-strengthened beams is discussed based on the experimental and numerical results in this section. The behaviour is evaluated in terms of the load–deflection curve, stiffness, ductility and crack patterns [14].

6.1 Load–Deflection Behaviour

The load–deflection curves of both control and strengthened beams from the experimental tests were also verified by the numerical simulations. The control beams were linearly behaving up to the yield load of around 55 kN and then they deform nonlinearly until they reach an average ultimate load of near to 66 kN. The corresponding mid-span deflection was 4.9 mm. Conversely, the reinforced beams revealed better results after the first cracking phase. The effect of the presence of CFRP U-wrap increased the load capacity thereby the average ultimate load was about 100 kN which was an increment about 50–52%). The deflection at the ultimate load substantially increased to 16.7 mm, indicating an improved deformation capacity. The numerical results matched well with the experimental trends, validating the analytical model.

6.2 Stiffness Behaviour

The stiffness was determined from the slope of load–deflection curve at the early stage. The control beams had a mean stiffness of about 13.6 kN/mm, and the strengthened beams were on average less stiff, 6.0 kN/mm. This drop is due to the higher flexibility allowed by the CFRP system, which can deform more before failure [15]. Although the stiffness of the strengthened beams were lower and the values of energy absorption were larger, they exhibited the best performance in load carrying capacity

6.3 Ductility Behaviour

Ductility was computed as the ratio of the ultimate deflection to the deflection at yield. The control beams had a mean value of ductility index of about 2.3, while the value of the strengthened beams was close to 2.35–2.4. It means that the CFRP strengthening method yields superior increase in load-

carrying capacity without losing the ductility. Since the reinforced beams can undergo greater deformation, they are considered more dependable in severe loading conditions.

6.4 Crack Behaviour

The observed crack patterns in the beams showed a distinct variation between the control and the strengthened samples. In the beams without strengthening, cracks started at the tension zone and propagated quickly to the compression zone, leading to fewer, wider cracks with a depth of 150–155 mm. In retrofitted beams the CFRP U-wrap successfully contained the crack propagation. The cracks were shallower and more distributed having a mean value of about 110–130 mm. The addition of CFRP enhanced stress redistribution and retardation of crack growth, and thus increased the structural performance.

6.5 Comparison of Control and Strengthened Beams

A comparison of the control and the CFRP U-wrap strengthened beams indicates the efficiency of this method of strengthening.

- The ultimate load was raised from about 66 kN for the control to 100 kN for the strengthened, which is an enhancement of 51%.
- The deflection at ultimate load was significantly improved from 4.9 mm to 16.7 mm.
- The stiffness was reduced in strengthened beams, as they were more deformable, but this led to enhanced energy dissipation.
- The strengthening did not significantly alter the ductility index, indicating that the ductility of the structure was not compromised.
- Depth of crack was minimized and distribution of cracks was enhanced in the strengthened beams. The CFRP strengthened beams showed clearly better overall performance than the control beams for the load capacity, deformation behavior, and crack resistance. The results demonstrate that the strengthening method employed is suitable for enhancing flexural performance of RC beams.

7 Summary

In this paper, an investigation on the bending performance of RC beam strengthened by Near-Surface Mounted (NSM) CFRP U-wrap is conducted by means of experiment and FEM study. Beams were subjected to four-point loading to assess the load–deflection response, stiffness, ductility, and crack patterns. The strengthened beams exhibited a significant enhancement in structural performance over the control specimens. The numerical results were in good agreement with the experimental ones, which proved the modelling approach for the strengthened system.

8 Conclusions

The test results confirmed that the NSM CFRP U-wrap method can be used to improve significantly the flexural behaviour of RC beams. The strengthened beams showed an enhancement of the ultimate load carrying capacity from the range of 66 to 100 kN by about 51% than that of the control beams. A significant increase in deformation capacity was also observed as the deflection at the ultimate load was increased from 4.9 mm to 16.7 mm. Although the ductility index increased, it remained almost the same value of approximately 2.3–2.4 for both specimens, which indicates that the method of strengthening doesn't affect ductility. Crack behaviour was enhanced as the crack depth was reduced from about 155 mm in control beams to close to 120 mm in the strengthened beams, together with a more homogeneous crack distribution. The numerical results were in good agreement with experimental results, validating the developed finite element model. In general, the strengthening method was found to be successful for the improvement of load carrying capacity, deformation performance, and crack control of RC beams.

9 Future Recommendations

Further investigations may be conducted for enhancement of the CFRP strengthening method with different parameters such as the thickness of the sheet, the orientation of the fiber and the bonding conditions. Studies of varying size of beams, the type of reinforcement and the loading regime would be useful in generalising the results. The long-term performance of CFRP strengthened beams exposed to environmental conditions, such as changes in temperature and moisture, needs to be investigated as well. Moreover, more sophisticated numerical models (e.g., accounting for bond-slip behaviour and realistic interface properties) can be developed to increase the accuracy of the predictions and to better represent the actual structural behavior.

Declarations

Author Contribution

The Near-Surface Mounted (NSM) CFRP U-wrap technique is an efficient and reliable method for strengthening reinforced concrete beams. Experimental studies consistently demonstrate significant improvements in load-carrying capacity, stiffness, crack control, and overall structural performance. Analytical models closely match experimental observations, making them suitable for design and performance prediction. The addition of CFRP U-wraps enhances the anchorage of NSM reinforcement, delays debonding, and improves shear resistance, resulting in safer and more durable RC structures.

Data Availability

“The data generated and/or analyzed during this study are available from the authors upon reasonable request.”

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Figures

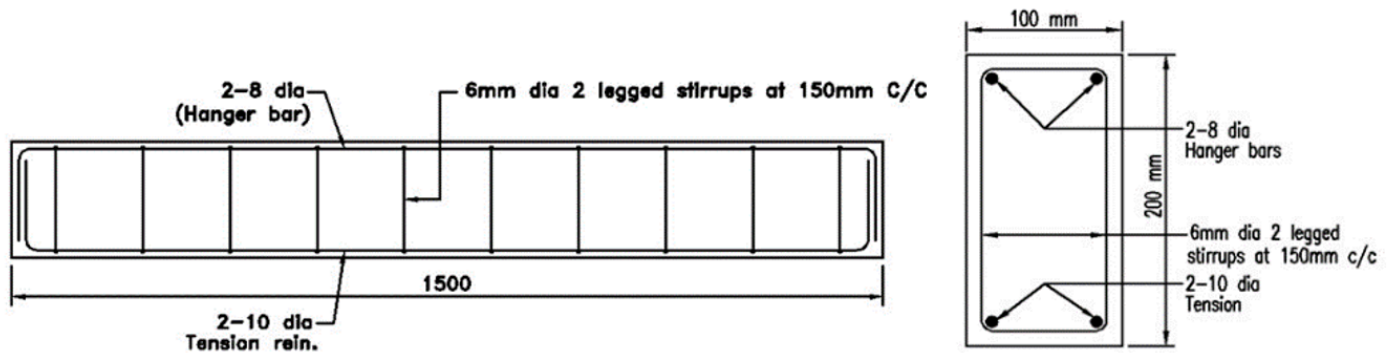


Figure 1

Longitudinal and cross section of RC beams

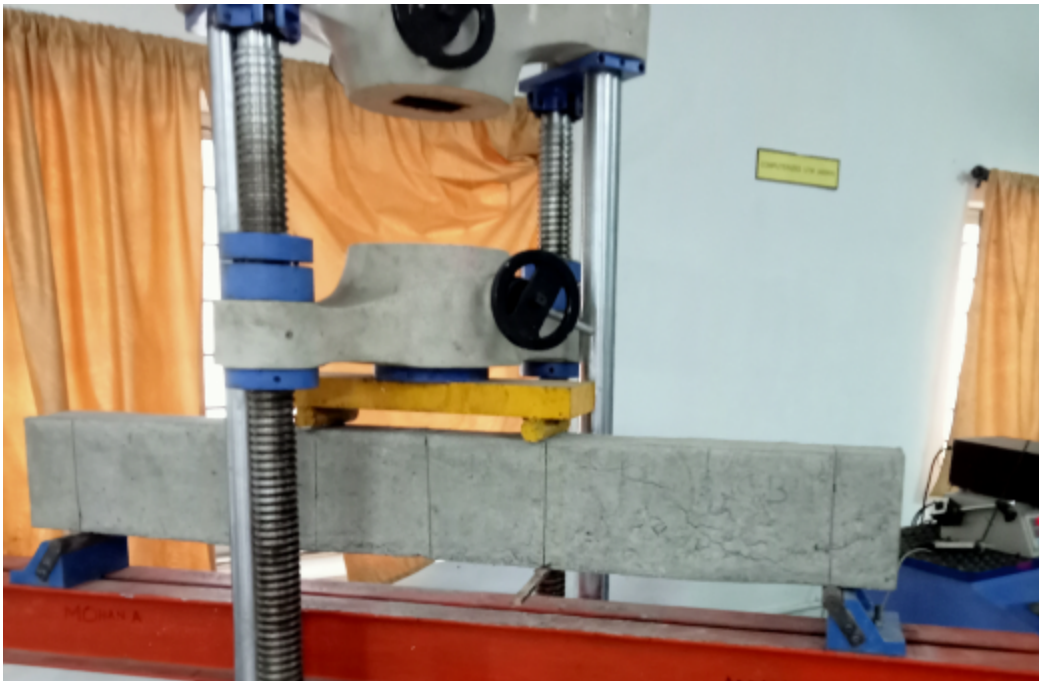


Figure 2

Test Specimen of Control beam

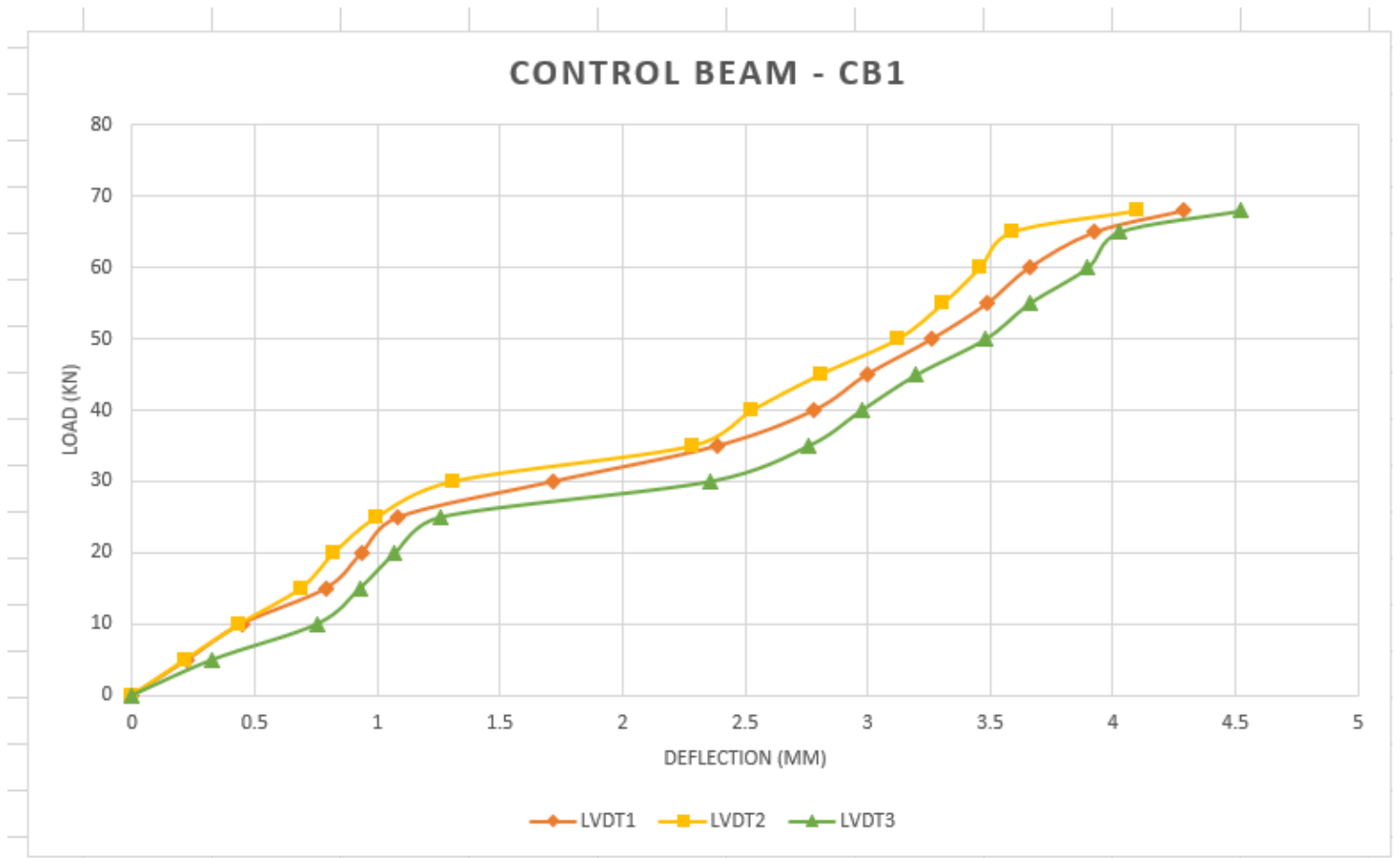


Figure 3

Load deflection of Control beam



Figure 4

Test specimen of U-Wrap beams

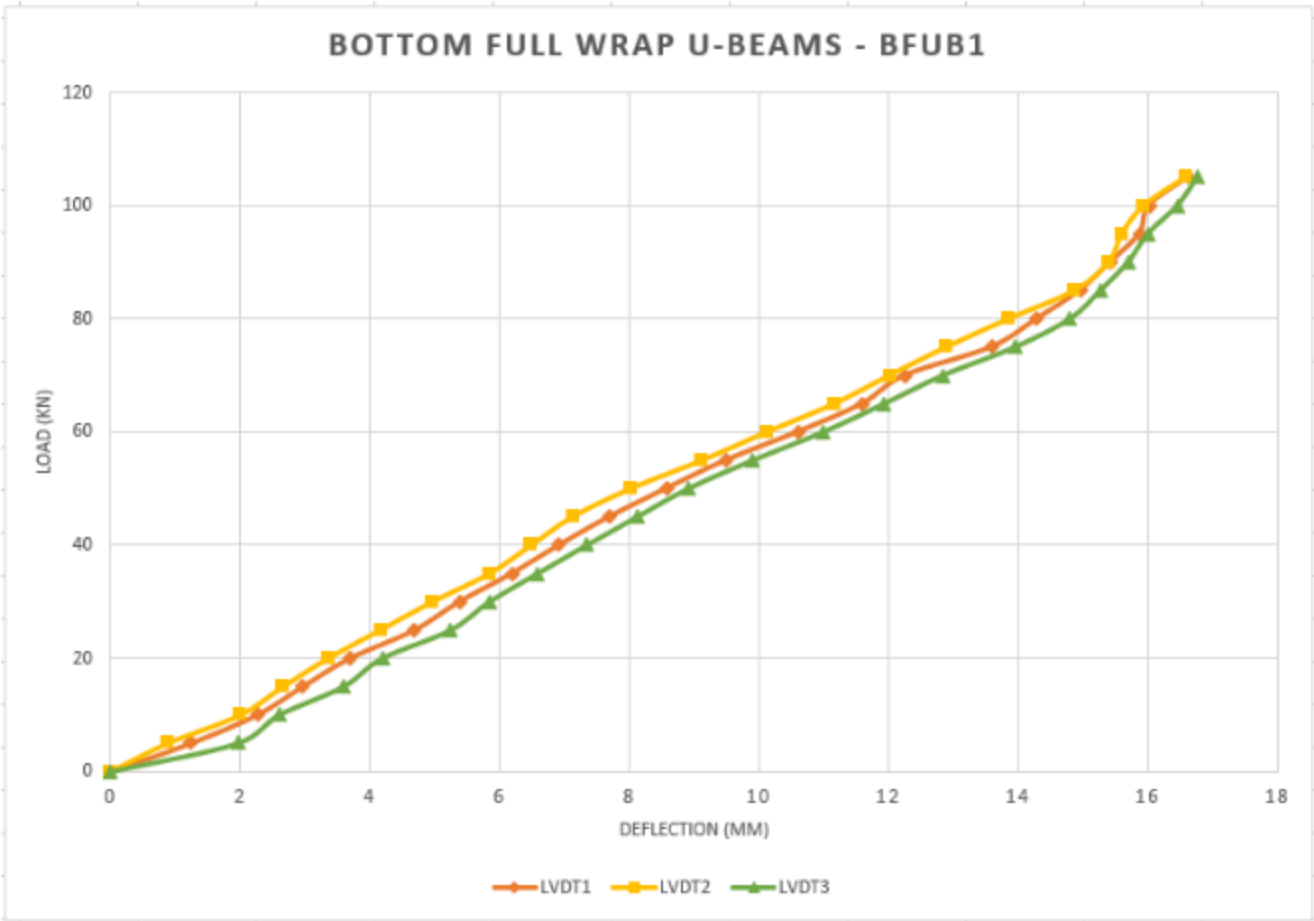


Figure 5

Load deflection of U-Wrap beams

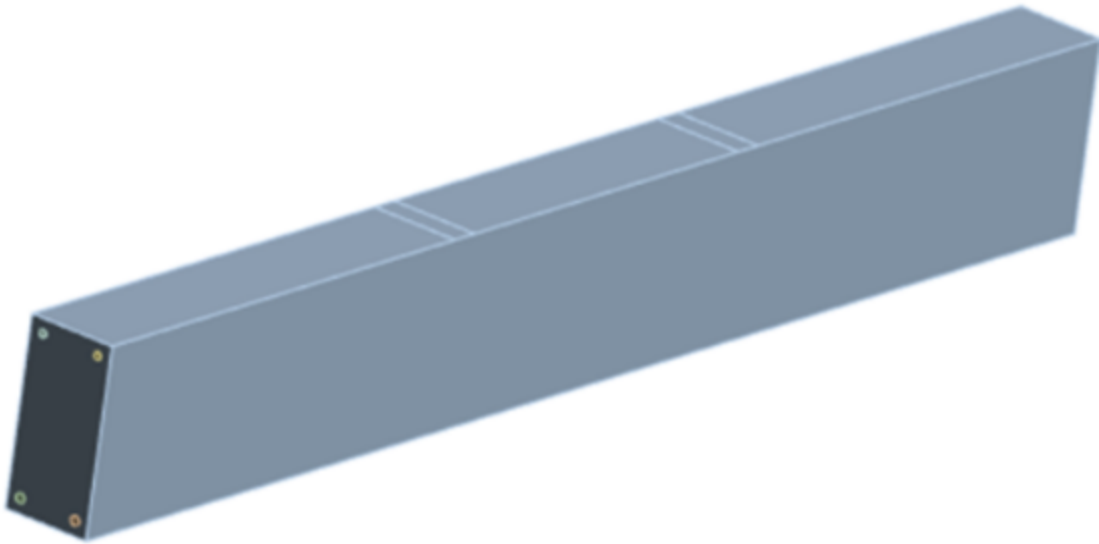


Figure 6

Ansys result for Control beam

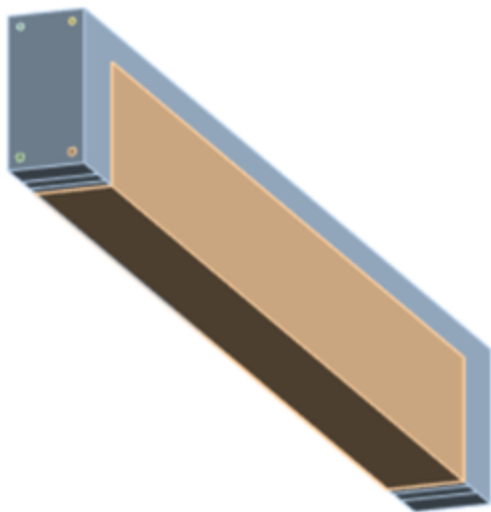


Figure 7

Ansys result for U- Wrap beams

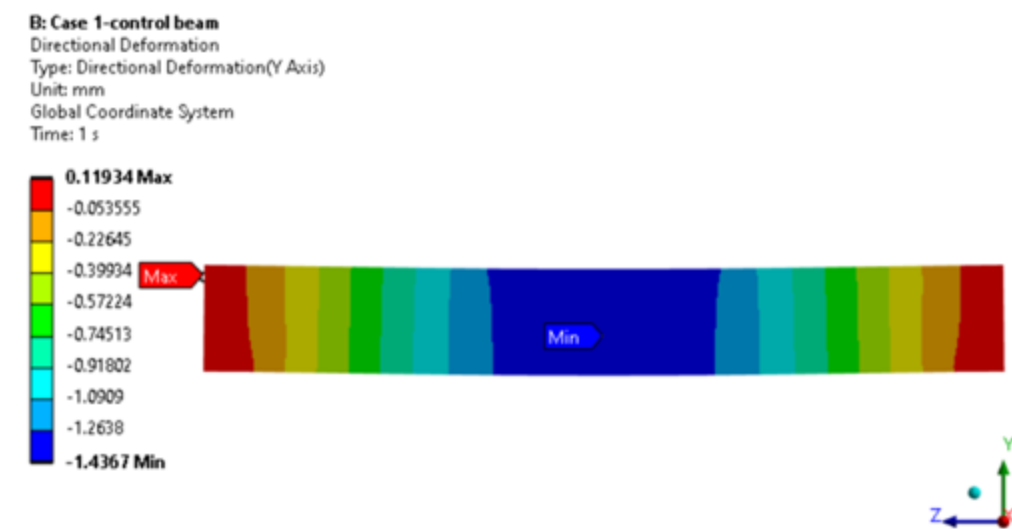


Figure 8

Analysis report for Control beam

C: case2-Bottom full U-Wrap

Directional Deformation

Type: Directional Deformation(Y Axis)

Unit: mm

Global Coordinate System

Time: 1 s

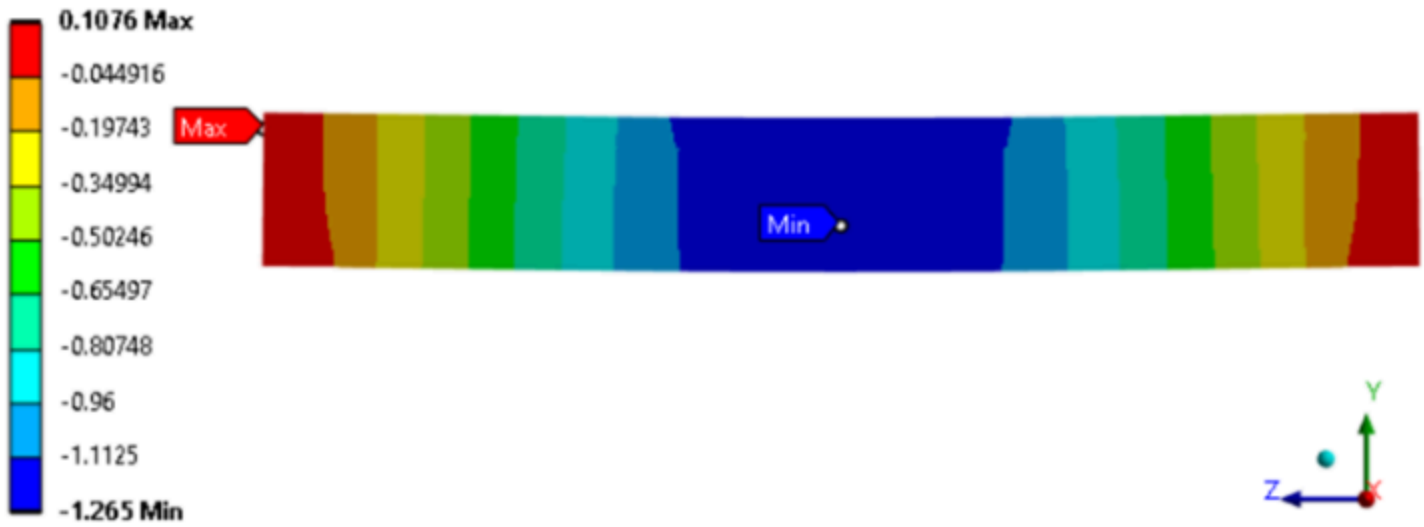


Figure 9

Analysis report for U-Wrap beams

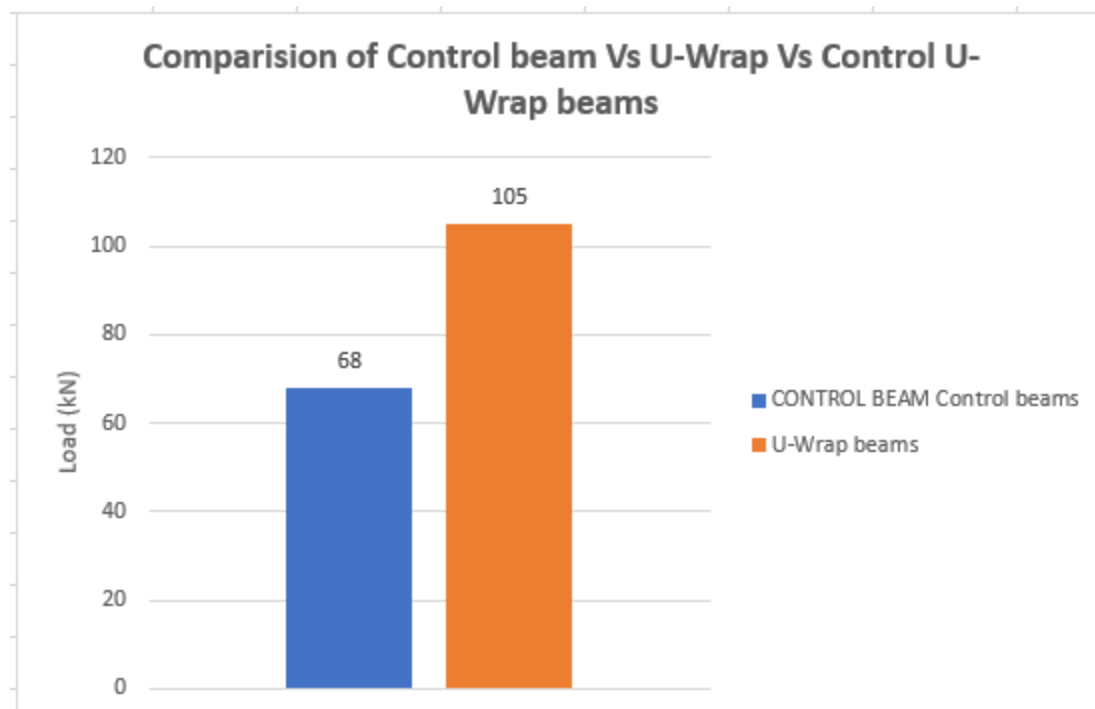


Figure 10

Comparison of Control and U-Wrap beams

