Performance of Timber Strengthened using Epoxy and different types of steel wire

Amr A. Gamal, Tarik S. El-Salakawy, Taha A. El-Sayed

Abstract—Timber is a renewable material that overcomes pollution problems and is characterized by its lightweight and high tensile strength resistance. For several decades, timber was used in many daily life applications in buildings. The problem of increasing its strength and overcoming its decay problems still limits its use in other daily application in construction. This led to investigate the use of timber coated with Epoxy material to strengthen the wood and avoid decay problems as well as using low cost strengthening techniques such as thin wire, rolled wire, and steel wire mesh reinforcement with Epoxy to improve its mechanical performance. The test program in this study was designed to investigate the effect of using strengthened timber in a two-phase program. Using epoxy proved to be very successful in eliminating decay problems. Use of wire with Epoxy proved to be very successful in enhancing flexural strength of timber beams.

Index Terms— Strengthened timber, Epoxy coated timber, wire coated timber, mechanical properties of strengthened timber, wire mesh strengthened timber, thin wire timber.

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1 INTRODUCTION

Wood is a renewable material and its use in construction has many advantages regarding reduction of building weight compared to the ordinary concrete building, in addition, to its high tensile strength resistance. Construction has a high environmental impact so it's important to use natural resources and re-use existing ones [1]. Wood is a complex material, due to its heterogeneity and anisotropy (fibers orientation, rings, presence of nodes, deficiencies, etc.) [2]. Raposo et al [3], found that the wood water content influences the behaviour and properties of wood. This is due to changes such as retraction or expansion of wood, and consequent distortions and warping, which affect the strength and elastic modulus. When the water changes occur above the wood fibers saturation point, the properties remain practically unchanged.

A. Borri and M. Corradi [4] presented an experimental study on the strengthening of wood beams under bending loads using very high strength steel cords. Mechanical tests on the strengthened wood showed that external bonding of steel fibers produce high increases in flexural stiffness and capacity.

Marco Corradi et al [5] studied the use of stainless-steel profiles in retrofitting timber structural elements within historic structures by reviewing the development of the retrofitting methods and existing experimental studies on the mechanical behavior of timber structures reinforced with stainless steel.

This study focused on enhancing mechanical properties of timber: under compression and flexure loads using several techniques of wire strengthening, while coating timber with epoxy to enhance bonding and to isolate wood from external conditions. The investigations also aim to control volumetric changes such as retraction or expansion, while providing protection against external environmental conditions and decay.

2 EXPERIMENTAL PROGRAM

The aim of the testing program is to study physical and mechanical properties and investigate stress strain behavior under axial loading. Also, study the effect of epoxy and steel wire mesh with timber on compression and flexure strength. The purpose of phase 1 focused on checking the effect of additives on wood to improve its behavior through comparison of the compressive strength of wood samples and wood coated with different types of epoxy to establish whether the compressive and flexural strength increases when using Epoxy or not, and to select the best type of Epoxy that will give best results with wood.

2.1 MATERIAL PROPERTIES

2.1.1 WOOD

The used samples are of type Muski wood, the mechanical properties of the used wood have been adopted from testing as follows in section 3.1.1.

2.1.2 WIRE MESH PROPERTIES

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wire mesh have been used to reinforce and confine the wood samples, the wire-mesh reinforcement specifications are listed below [6].

- Wire diameter 1 mm.
- Type of mesh is welded wire galvanized mesh
- Size of mesh openings 5 mm

Fig.1 Ferro-cement wire mesh.

2.1.3 Epoxy

Epoxy was used to enhance the mechanical properties of the wood samples as well as to resist the decay problems, also to increase the bond between the wood and the used different types of reinforcement, Two types of epoxy have been used Epoxy 129 and Epoxy 150 [7], as shown in fig. 2 and its mechanical properties are listed in table 1 and 2.

TABLE 1

Error! No text of specified style in document. Properties of epoxy 129

Initial setting time	3 hours
Final setting time	18 hours
Full hardness	after 7 days
Recoating time	12 - 24 hours
Thinner	(10% when needed)
Min. application temp	8°C

TABLE 2

Properties of epoxy 150

Initial setting time	8 hours
Final setting time	24 hours
Full hardness	after 7 days
Recoating time	18-24 hours
Thinner	KEMSOLVE 3, KEMSOLVE 4 (5% when needed)
Min. application temp	5°C

Fig.2 Kemapoxy129 and 150 [7]

2.2 Preparation of Specimens and Samples Description

2.2.1 Phase: I

samples of wood of cross section 70 mm x 70 mm and length 250 mm, samples dimensions are shown in fig. 3.

Paint the samples with epoxy 129 and wait for 10 minutes and paint a second layer. The samples were left for 12 hours to gain its strength, as shown in Fig. 4.

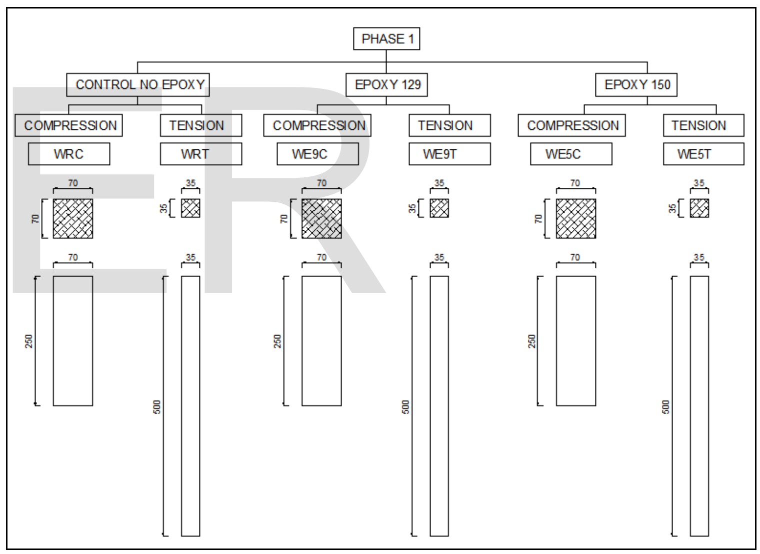


Fig. 3: Phase I, configuration and samples dimensions.

Fig. 4 (a): Compression and flexure samples, (b) : Samples with Epoxy 129

TABLE 3
SAMPLES NOTATIONS, DESCRIPTIONS AND DIMENSIONS FOR Phase I

Samples	Samples Description	Samples Dimensions (mm)
WRC	Wood Reference for compression test	70X70X250
WRT	Wood Reference for flexural test	35X35X500
WE9C	Wood with Epoxy 129 for compression test	70X70X250
WE9T	Wood with Epoxy 129 for flexural test	35X35X500
WE5C	Wood with Epoxy 150 for compression test	70X70X250
WE5T	Wood with Epoxy 150 for flexural test	35X35X500

2.2.2 PHASE: II

In the second phase, samples of wood strengthened with different types of reinforcement, See Fig 5, 8, were tested for compression and flexure. The three wood beams already coated with epoxy 150. The difference between the three beams is the used strengthening type, first sample was coiled with thin wire, the second one was coiled using rolled wire, while the third was wire mesh coiled.

Sample preparation before test (Reference with Epoxy and wire). Paint Epoxy and warp the wire around wood; wait for 10 minutes and paint another layer of Epoxy; let it to set for 12 hours to gain its strength, as shown in Fig. 6.

The bearing surface of the testing specimen shall be wiped clean and any loose material removed from the surface. The axis of the specimen was aligned with the steel plates. As shown in Fig. 7, The load was applied slowly without shock and increased continuously until failure and crushing of specimen and no greater load can be sustained. The maximum load applied to the specimen was recorded. Also three-point load tests was used to determine the max flexural loads.

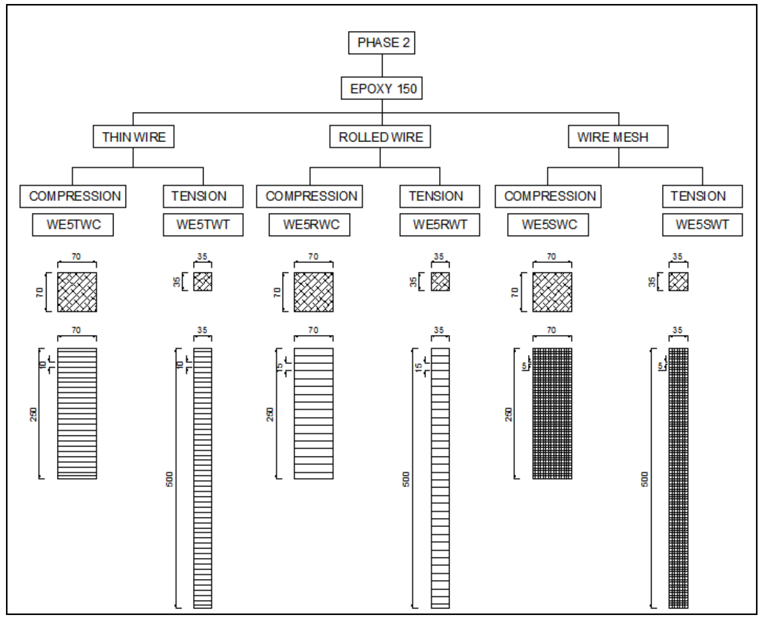


Fig. 5: Phase II, configuration and samples dimensions

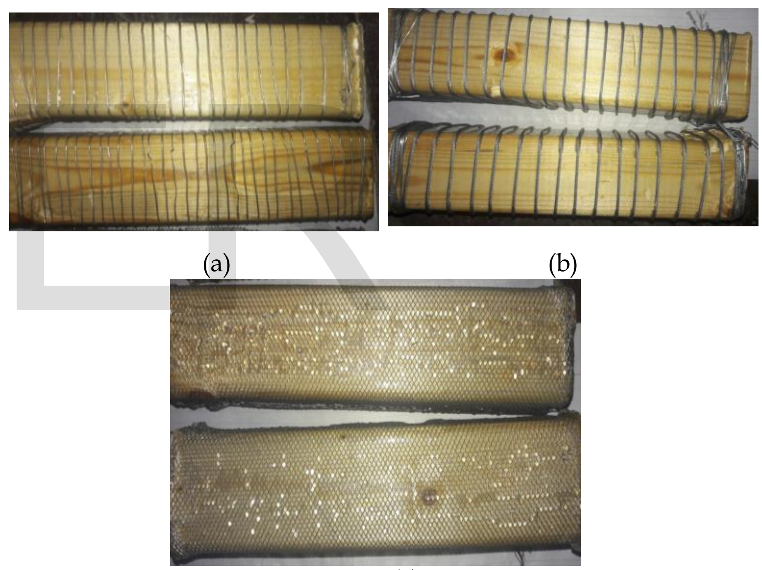

(a) (b)
(c)
Fig.6 a) Wood wrapped with thin wire samples, b)wood wrapped with rolled wire samples, c)Wood wrapped with wire mesh samples


Fig. 7 : Compression test setup

Fig. 8: Wood samples

Table 4
Samples notations, descriptions and dimensions Phase II

Samples	Samples Description	Samples Dimension(mm)
WE5TWC	Wood with Epoxy 150 reinforced with thin wire for compression test	70X70X250
WE5TWT	Wood with Epoxy 150 reinforced with thin wire for flexural test	35X35X500
WE5RWC	Wood with Epoxy 150 reinforced with rolled wire for compression test	70X70X250
WE5RWT	Wood with Epoxy 150 reinforced with rolled wire for flexural test	35X35X500
WE5SWC	Wood with Epoxy 150 reinforced with wire mesh for compression test	70X70X250
WE5SWT	Wood with Epoxy 150 reinforced with wire mesh for flexural test	35X35X500

3. Results and Discussion

3.1 Phase I

3.1.1 Compression Test Results

Wooden sections 70mm X 70mm X 250mm were subjected to axial loading using a compression machine EIE type. Compressive strength results indicated that the compressive strength in WE9C (wood Epoxy) specimens increased by 24 % when compared to reference specimens WRC which may be attributed to the confinement of the epoxy coating to the wooden prism surface. WE5C (wood coated with Epoxy 150) specimens increased by 26% when compared to WRC specimens. This may be attributed to the confinement of the wooden prism specimens surface in addition to the existence of a higher percentage of solid materials in Epoxy 150 rather than Epoxy 129. It should be noted that the failure mode in WRC subgroups exhibited crushing of the wood fibers at the mid-section of the wooden prism, exhibiting a lateral crack at mid-section which is considered the weakest and least confined section. See Table 5 & Figures 9, 10.

Table 5
Compressive strength test results for phase I

Samples	Description	Experimental Ultimate Failure Load Pc Exp. (KN)	Enhancement in failure load compared to the control sample %
WRC (KN)	control	151.85	----
WE9C (KN)	Epoxy 129	187.82	124%
WE5C (KN)	Epoxy 150	191.60	126%

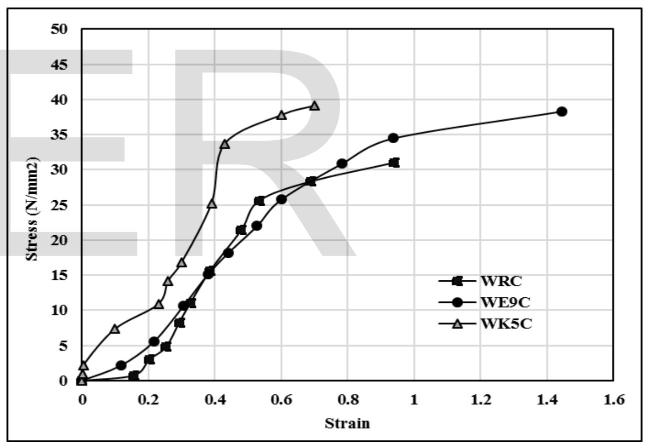


Fig. 9 : Effect of stress (compression) on strain for phase I

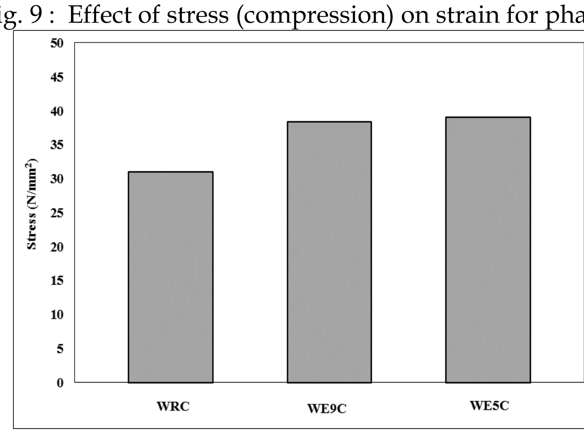


Fig. 10 : compressive strength test results for phase I

3.1.2 Flexural Test Results

Flexural strength results show that WE9T (wood Epoxy) specimens showed an ultimate failure load higher by 10% when compared to reference specimen's WRT. This may be attributed to the existence of a thin layer of the Epoxy coating surrounding the wooden beam surface, which resulted in a corresponding increase in flexural strength. Wooden beams coated with Epoxy 150 (WE5T) showed an increase in the ultimate flexural failure load by 28% when compared to WRT specimens. This may be attributed to the confinement of the wooden beams specimens with Epoxy resin especially at the top and bottom fibers of the timber surface. It should be noted that WE5T showed an increase in the ultimate flexure failure load by 18%, which was attributed to the existence of a higher percentage of solid materials in Epoxy 150 samples when compared to solid materials in Epoxy 129 samples. This trend was in agreement with the compressive strength results mentioned in the previous section. It should be noted that WRT, WE9T and WE5T wooden beam exhibited a splintering tension failure mode which is characterized by a highly irregular vertical crack starting at the bottom tension fibers and extending to the top fiber. Complete separation of the wooden beam was not reached. See Table 6 & Fig. 11.

Table 6
Flexural strength test results for phase I

Samples	Experimental Ultimate Failure Load PF Exp. (KN)	Enhancement in failure load %
WRT (KN)	5.20	----
WE9T (KN)	5.71	110%
WE5T (KN)	6.63	128%

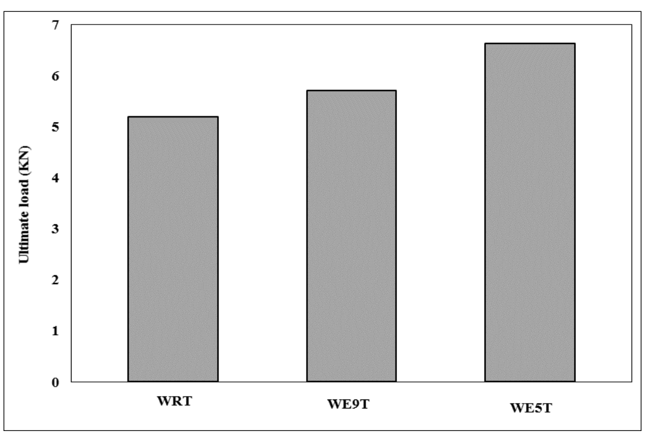


Fig. 11: Flexural strength test results for phase I

3.1.3 Schmidt Hammer Test Results

Schmidt hammer results clearly reflect the surface hardness of the Epoxy coated wood specimens where WE9 exceeded the average readings of the reference wood specimens by 5.6%. Meanwhile, WE5 exceeded reference wood specimens by 29.56%. Wood coated with Epoxy 150 gave the highest results which was a reflection of the compression and flexural results indicated in Table 7 and Fig. 12. Schmidt hammer is used to measure the hardness of the surface of wood sample. The test was carried out according to ASTM, C., 597 [8]

Table 7
Schmidt hammer Rebound Numbers for Phase I

Sample	WR	WE9	WE5
N1	20.0	29.0	23.0
N2	24.0	30.0	25.0
N3	25.0	30.0	23.0
N4	23.0	29.0	22.0
N5	26.0	30.0	25.0
N6	23.0	31.0	28.0
N7	22.0	29.0	27.0
N8	21.0	29.0	23.0
N9	24.0	30.0	25.0
N10	22.0	31.0	22.0
N avg.	23.0	29.8	24.3

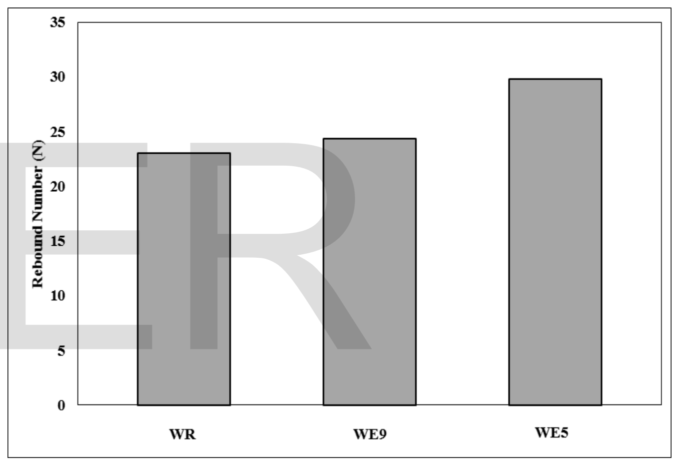


Fig. 12 : Average Schmidt hammer Rebound Numbers for Phase I

3.2 Phase II

3.2.1 Compression Test Results

Wooden prisms with dimensions 70mm X 70mm X 250mm and coated with epoxy 150 in phase two were subjected to axial loading using a compression testing machine. Using wooden prisms wrapped with thin wire 1mm in diameter (WE5TWC) resulted in an increase in the compressive strength by 30% when compared to reference specimen which primarily indicates the effectiveness of using thin wire with wood to act as a single unit and the strong cohesion achieved when using Epoxy to bind wood with thin wire. Wooden prisms wrapped with rolled wire (WE5RWC) which was more expensive when compared to thin wire resulted in an increase in the compressive strength by 31% compared to WRC specimens, although the cross section of the rolled was 3mm in diameter. This was possibly attributed to the lack of proper adhesion between the rolled wire and the wooden prism due to the high stiffness of the rolled wire which resulted in hump in the rolled wire, which makes it impossible to be properly attached the rolled wire at the sides of the wooden prism. The only attachment in that case, was at the corners of the wooden prism. Wooden prisms wrapped with steel wire mesh (WE5SWC) gave highest compressive strength results which increased by 34% when compared to reference wood prisms WRC. This was attributed to the fact that the wire mesh could be properly attached to the wooden prism using Epoxy 150 in a two-layer coating and the two-dimensional support of the wire mesh improves the bond between the wooden prism and the wire mesh and provides better support and confinement. It should be noted that the failure mode in WRC subgroups exhibit a crushing of the wood fibers at the mid-section, which in turn, exhibits a lateral crack at mid-section which is considered the weakest and least confined section. See Table 8 & Figures 13,14.

Table 8

Compressive strength test results for phase II

Samples	Experimental Ultimate Failure Load Pc Exp. (KN)	Enhancement in failure load compared to the control sample %
WE5TWC (KN)	197.88	130%
WE5RWC (KN)	199.00	131%
WE5SWC (KN)	203.50	134%

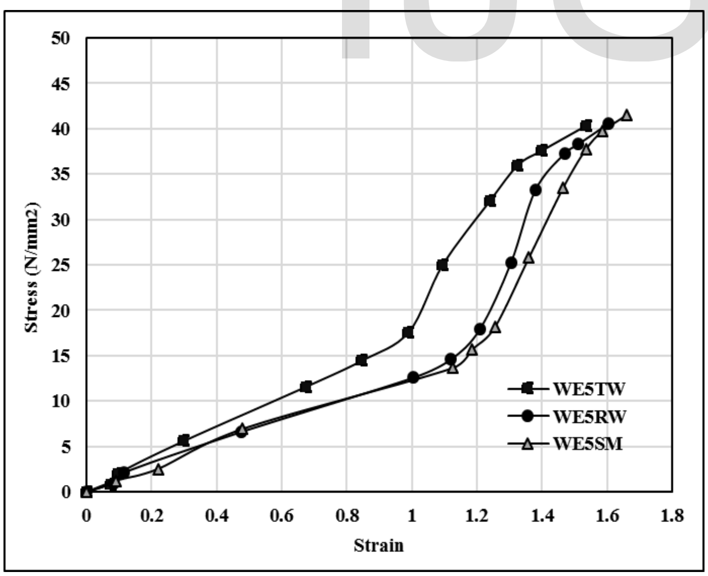


Fig. 13 : effect of stress (compression) on strain (Phase II)

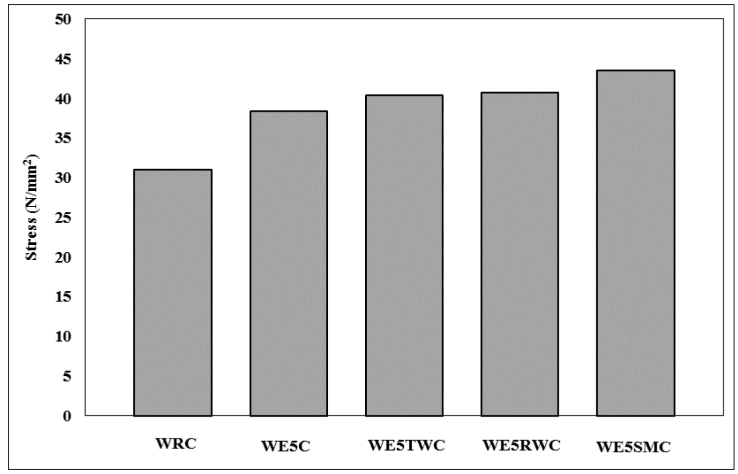


Fig. 14 : Compressive strength test results for phase II

3.2.2 Flexural Test Results

Wooden beams wrapped with thin wire 1mm in diameter (WE5TWT) resulted in an increase in flexural ultimate failure load by 37% when compared to reference specimen which primarily indicates the effectiveness of using thin wire with wood under flexure to act as a single unit. The failure mode in that case was characterized by a tension vertical crack 5mm at the bottom fibers that extended vertically upwards. Wooden beams wrapped with rolled wire (WE5RWT) showed an increase in the ultimate failure flexure load by 44% when compared to reference wooden beams WRT. The failure mode in that case was characterized by a tension vertical crack 3.5mm at the bottom fibers that extended vertically upwards. Wooden beams wrapped with steel wire mesh (WE5SWT) gave best results ultimate failure flexure load by 52% when compared to reference wooden beams WRT. The failure mode in that case was characterized by a tension vertical crack 2mm at the bottom fibers that extended vertically upwards. This was attributed to the fact that the wire mesh could be properly attached to the wooden prism using Epoxy 150 in a double layer coating and the two-dimensional support of the wire mesh improved the bonding between the wooden prism and the wire mesh and provided better support and confinement. It should be noted that, wooden beams coated with Epoxy and strengthened with different types of wire gave significant results when compared to reference wood beams as stated in Table 9 and Fig. 15.

Table 9: Flexural strength test results for Phase II

Samples	Description	Experimental Ultimate Failure Load PF Exp. (KN)	Enhancement in failure load compared to the control sample%
WE5TWT (KN)	Thin wire	7.10	137%
WE5RWT (KN)	Rolled wire	7.51	144%
WE5SWT (KN)	Wire mesh	7.88	152%

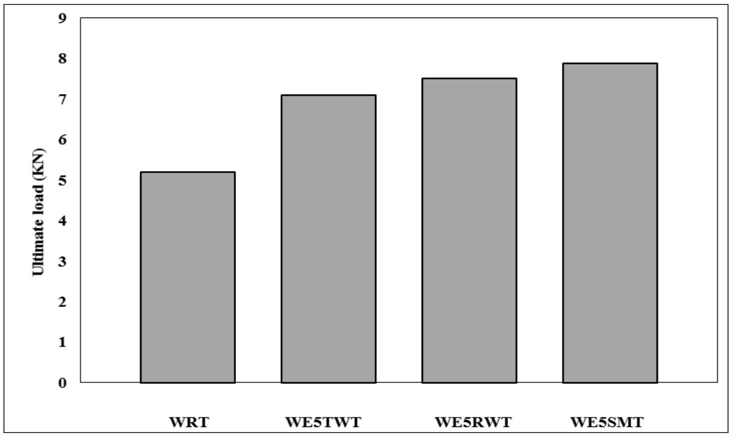
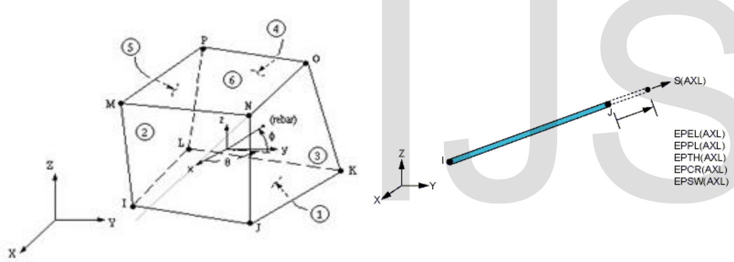


Fig. 15 : Flexural strength test results for Phase II

4. Non-linear finite element analysis study

Nonlinear finite element analysis was done to verify the obtained experimental results. These specimens were modeled and analyzed using ANSYS 15.0 [9].

4.1.1 Model Elements types



(a) (b)

Fig. 16 : Geometry of used element a) Solid65 b) Link 8

4.1.2 Modelling Material properties

The mechanical properties for element SOLID65 used in the analytical model which represent wood, was based on the stress strain curve developed from the experimental program, thus the model applied in the finite element analysis represents integrated characteristics of timber, epoxy and wire or steel mesh reinforcement.

4.2 Analytical Results and Discussion

4.2.1 Phase I

4.2.1.1 Analytical Compression Results

Compressive strength results indicate that the compressive strength in WE9C specimens increased by 20 % when compared to reference specimens WRC. WE5C specimens increased by 23% when compared to WRC specimens. See Table 10 & Figures 17, 18. Sample of analytical models and failure crack pattern for axial compression models are shown in figures 19.

Table 10

Analytical Compressive strength test results for Phase I

Samples	Analytical Ultimate Failure Load Pc Ana. (KN)	Enhancement in failure load compared to the control sample%
WRC (KN)	171.50	----
WE9C (KN)	205.80	120%
WE5C (KN)	210.31	123%

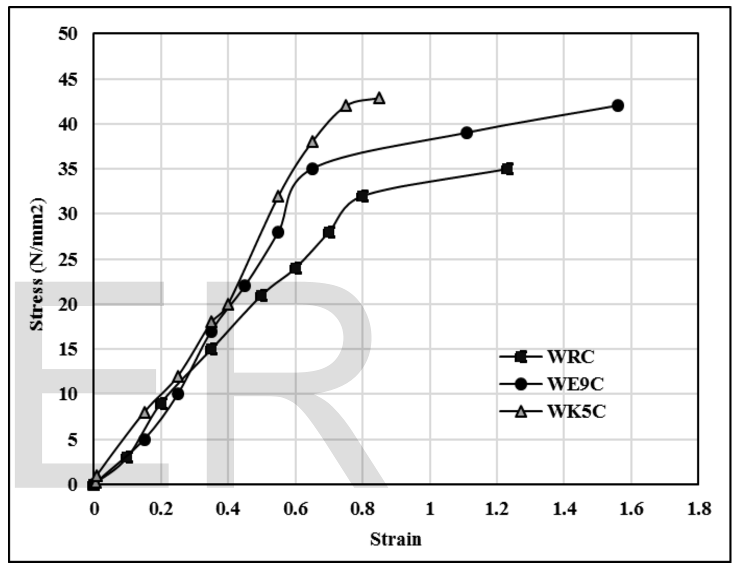


Fig. 17 : Analytical effect of stress (compression)on strain (phase I)

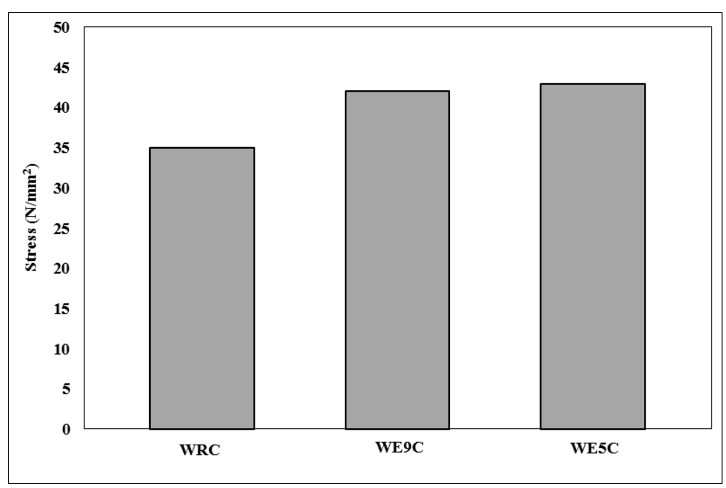


Fig. 18: Analytical Compressive strength test results for Phase I

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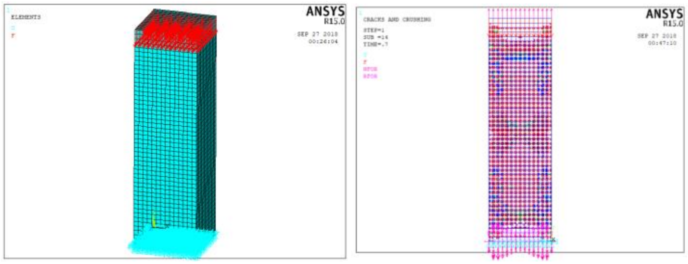


(a) (b)

Fig. 19: a) Ansys mesh, b) crack pattern

4.2.1.2 Analytical Flexural Results

Flexural strength results showed that WE9T specimens exhibited higher value than the reference sample by 12% when compared to reference specimen WRT. WE5T showed an increase in the ultimate flexural failure load by 28% when compared to WRT specimens. See Table 11 & Fig. 20. Sample of analytical models and failure crack pattern for flexural models are shown in fig. 21.

Table 11
Analytical flexural strength test results for Phase I

Samples	Analytical Ultimate Failure Load PF Ana. (KN)	Enhancement in failure load when compared to the control sample %
WRT (KN)	5.53	----
WE9T (KN)	6.22	112%
WE5T (KN)	7.09	128%

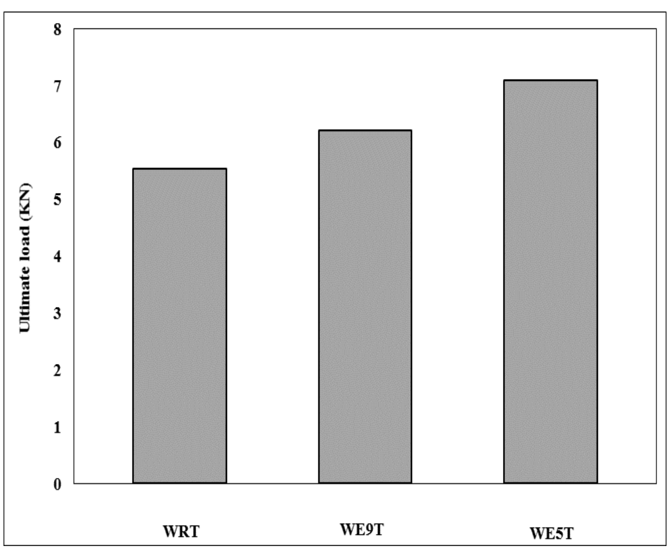
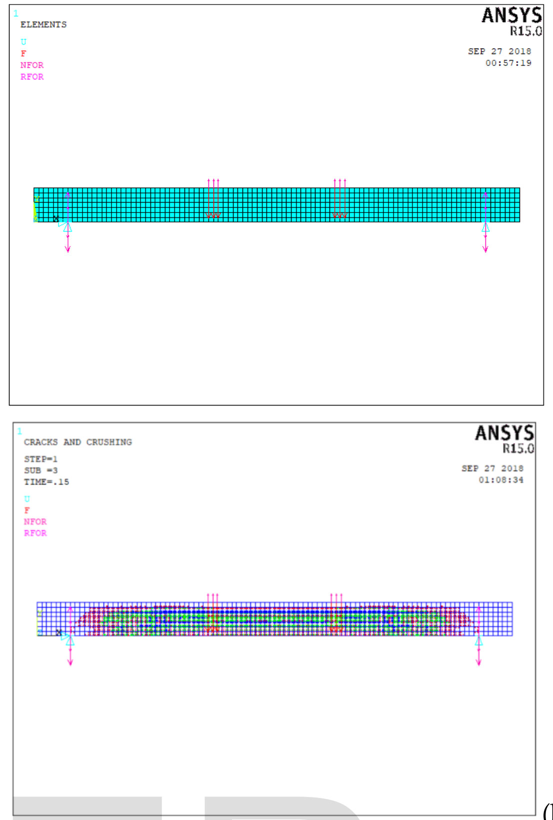


Fig. 20: Analytical flexural strength test results for Phase I



(a)

(b)

Fig. 21: a) Ansys mesh, b) crack pattern

4.2.2 Phase II

4.2.2.1 Analytical Compression Results

Compressive strength results indicated that the compressive strength increased by 23%, 26%, and 29% respectively regarding WE5TWC, WE5RWC, and WE5SWC when compared to the reference sample as shown in table 12 and fig. 22, 23. Aanalytical models and failure crack pattern for axial compression models are shown in figures 24,25 and 26.

Table 12

Analytical compressive strength test results for Phase II

Samples	Analytical Ultimate Failure Load Pc Ana. (KN)	Enhancement in failure load when compared to the control sample %
WE5TWC (KN)	210.95	123%
WE5RWC (KN)	216.73	126%
WE5SWC (KN)	221.28	129%

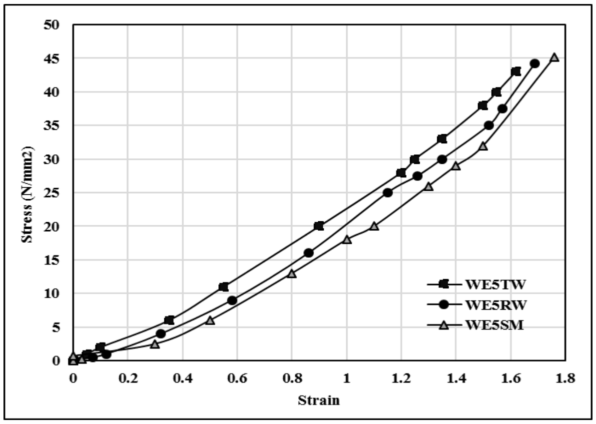


Fig. 22: Analytical effect of stress (compression) on strain for Phase II

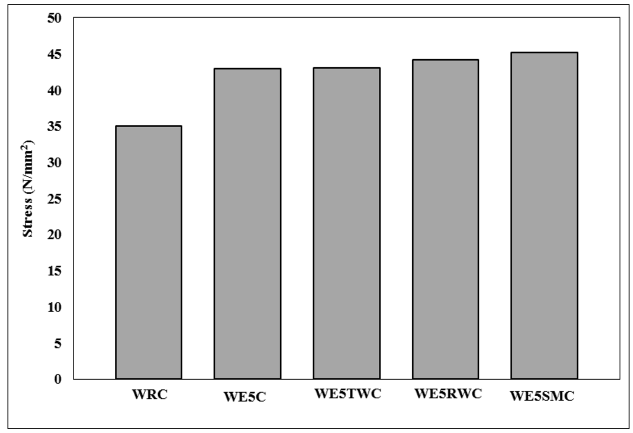
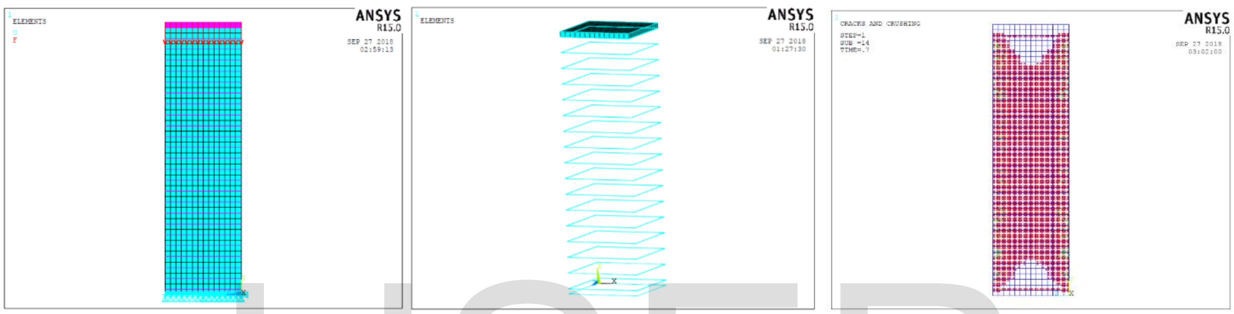
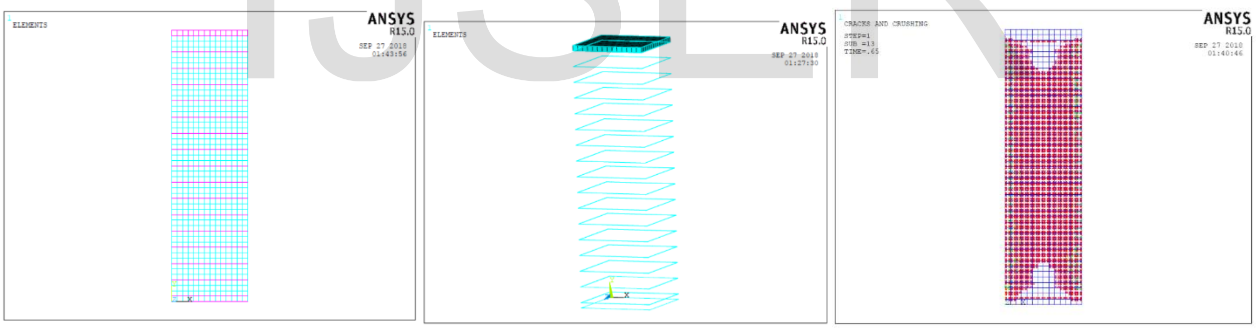


Fig. 23: Analytical compressive strength test results for Phase II



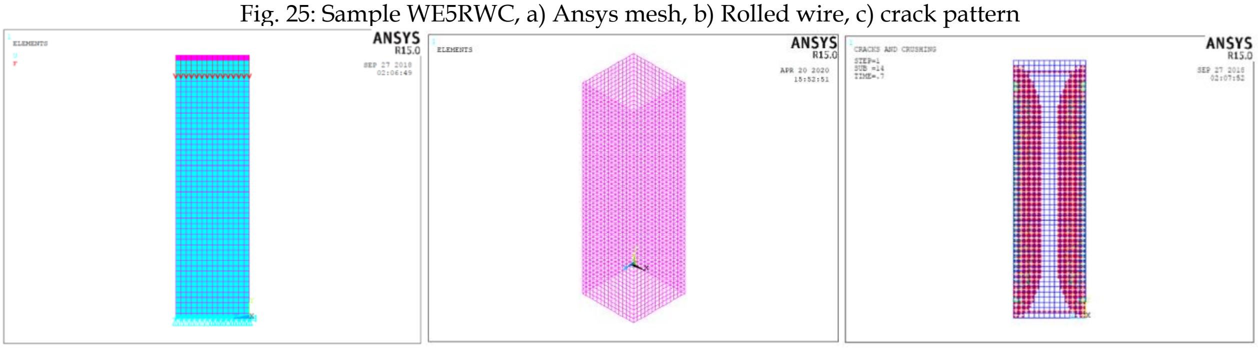
(a) (b) (c)

Fig. 24: Sample WE5TWC a) Ansys mesh, b)thin wire c) crack pattern



(a) (b) (c)

Fig. 25: Sample WE5RWC, a) Ansys mesh, b) Rolled wire, c) crack pattern



(a) (b) (c)

Fig. 26: Sample WE5SWC a) Ansys mesh, b) wire mesh, c)crack pattern

4.2.2.2 Analytical Flexural Results

Flexural strength results showed that the flexural strength

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increased by 33%, 43%,49% respectively regarding WE5TWT, WE5RWT, and WE5SWT when compared to the reference sample as shown in table 13 and fig. 27. Aanalytical models and failure crack pattern for flexural models are shown in figures 28,29 and 30.

Table 13: Analytical flexural strength test results for Phase II

Samples	Analytical Ultimate Failure Load PF Ana. (KN)	Enhancement in failure load when compared to the reference sample %
WE5TWT (KN)	7.34	133%
WE5RWT (KN)	7.89	143%
WE5SWT (KN)	8.25	149%

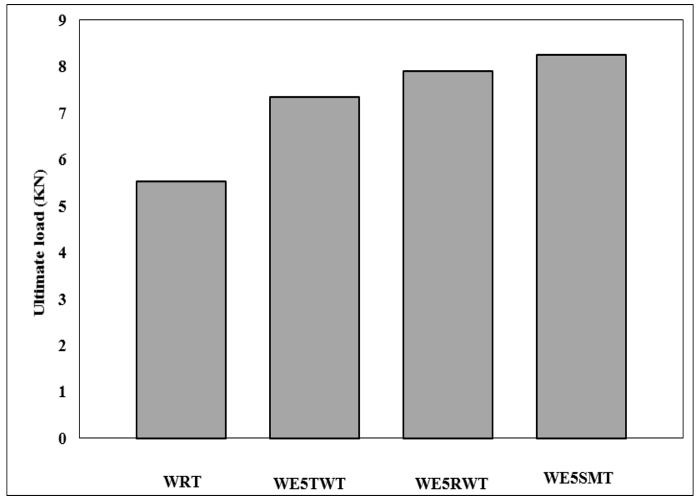
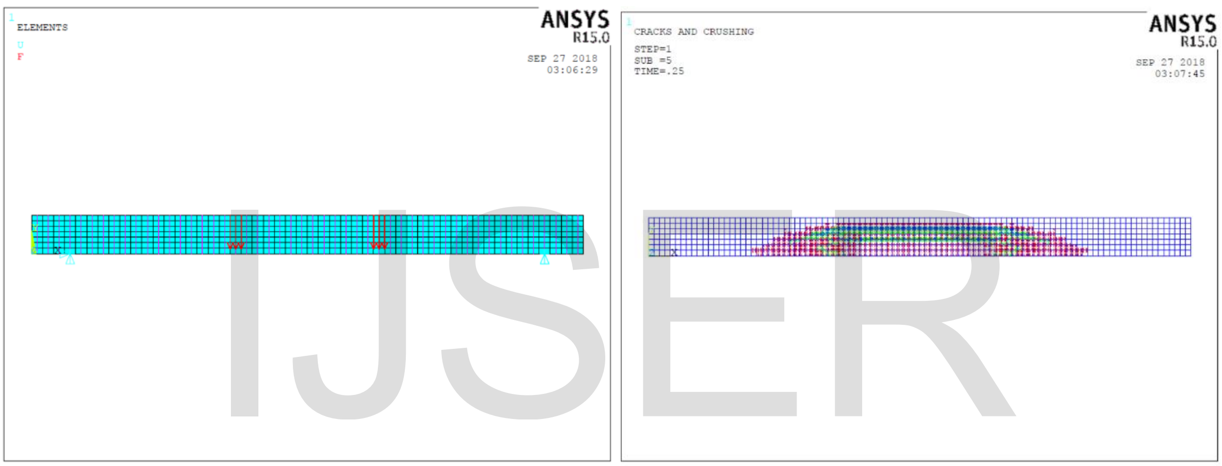
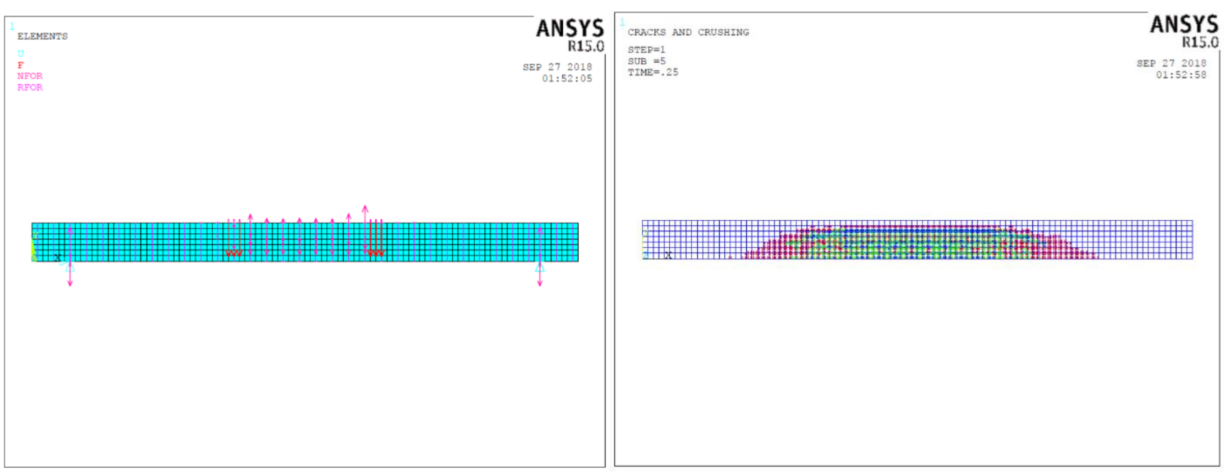


Fig. 27: Analytical flexural strength test results for Phase II



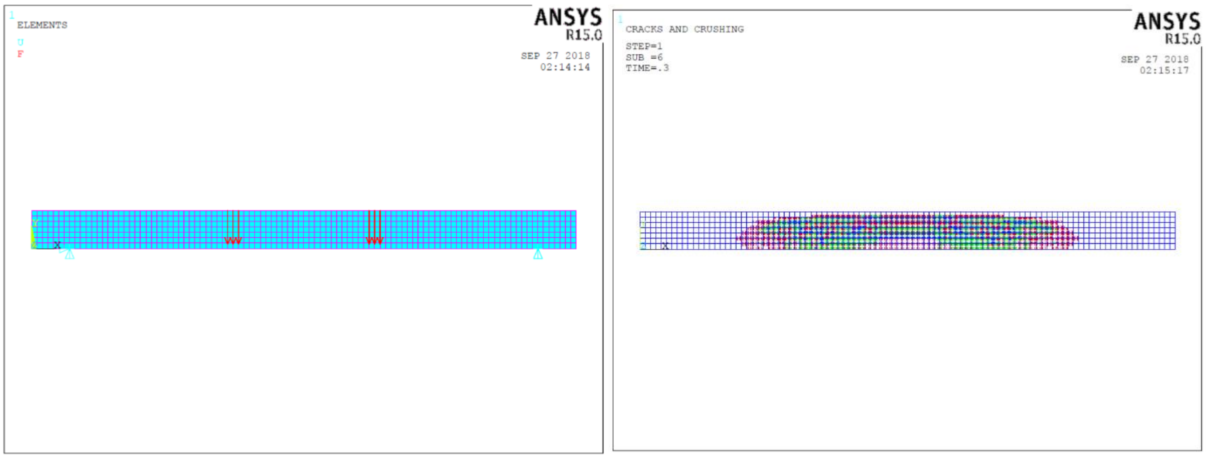
(a) (b)

Fig. 28: Sample WE5TWT, a) Ansys mesh, b)crack pattern



(a) (b)

Fig. 29: Sample WE5RWT, a) Ansys mesh, b)crack pattern



(a) (b)

Fig. 30 : Sample WE5SWT, a) Ansys mesh, b)crack pattern

5. Comparison between experimental and NLFEA results

First when comparing the compression test results of phase 1 and phase 2, it gives general trend indicates superiority of samples of phase 2 over samples of phase 1 as stated in section 3.2.1, these results may be attributed to additional confinement and strengthening of samples in phase 2, and the integrated effect of the epoxy and its effectiveness in binding the reinforcement to the wood samples to act as a complete matrix. These comparisons aim to show that the NLFEA models are available and can be used to predict the behavior of wood specimens. The finite element models were compared with the experimental specimens in term of ultimate failure loads, stress strain curves and crack patterns.

5.1 Ultimate failure load

5.1.1 Compressive ultimate failure load

Table 14 & 15 and Figures 31 & 32 showed an agreement to a certain extend between the experimental and analytical compressive, flexural failure loads where; Pc Ana. / Pc Exp. & Pf Ana. / Pf Exp. are quite close in values.

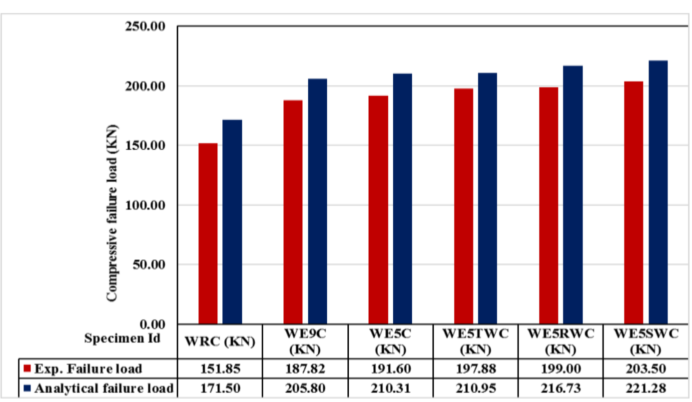


Fig. 31: Comparison between experimental and analytical compressive failure loads (KN).

Table 14

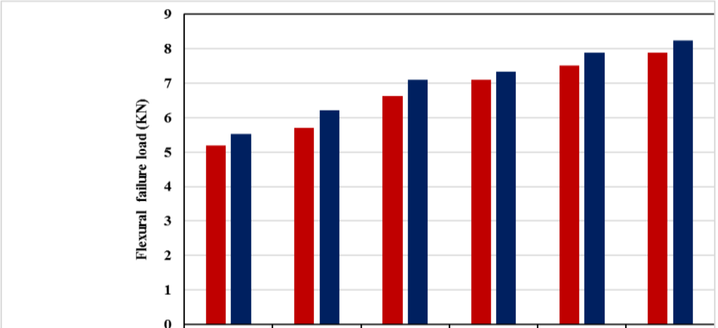
Comparison between experimental and analytical compressive ultimate failure loads

Samples	Experimental Ultimate Failure Load Pc Exp.	Analytical. Ultimate Failure Load Pc Ana.	PC Ana. / PC Exp.
WRC (KN)	151.85	171.50	1.129
WE9C (KN)	187.82	205.80	1.096
WE5C (KN)	191.60	210.31	1.098
WE5TWC (KN)	197.88	210.95	1.066
WE5RWC (KN)	199.00	216.73	1.089
WE5SWC (KN)	203.50	221.28	1.087

5.1.2 Flexural ultimate failure load

Table 15: Comparison between experimental and analytical flexural ultimate failure loads

Samples	Experimental Ultimate Failure Load Pc Exp.	Analytical. Ultimate Failure Load Pc Ana.	PC Ana. / PC Exp.
WRT (KN)	5.20	5.53	1.063
WE9T (KN)	5.71	6.22	1.089
WE5T (KN)	6.63	7.09	1.069
WE5TWT (KN)	7.10	7.34	1.034
WE5RWT (KN)	7.51	7.89	1.051
WE5SWT (KN)	7.88	8.25	1.047



Specimen Id	WRT (KN)	WE9T (KN)	WE5T (KN)	WE5TWT (KN)	WE5RWT (KN)	WE5SWT (KN)
Exp. Failure load	5.20	5.71	6.63	7.10	7.51	7.88
Analytical failure load	5.53	6.22	7.09	7.34	7.89	8.25

Fig. 32: Comparison between experimental and analytical flexural failure loads (KN).

6. Mode of Failure

At compression samples, failure happened at mid-longitudinal section due to confinement at top and bottom fibers with respect to loading plates. This trend of mood of failure was observed in all wood specimens with and without Epoxy.

At flexure samples, failure happened at bottom fiber of wooden beam and progressed vertically up ward and till complete failure. it is logically to note that failure mood in this case is tension failure at the bottom fiber of wooden beam. This trend of mood of failure was observed in all wood specimens with and without Epoxy.

Failure in compression : wood reference with Epoxy

Failure in flexure : wood reference with Epoxy

Failure in flexure: wood reference using Epoxy with thin wire

Failure in compression: wood reference using Epoxy with thin wire

Failure in compression : wood reference using Epoxy with rolled wire

Fig. 33: modes of failure of wood samples.

7. Conclusion

- Epoxy 129 increased compressive strength by 9.4% and by 9.4% in flexure more than the wood reference and this proves that Epoxy has an effective role in strengthening wood member in compression and flexure.
- Epoxy 150 increased compressive strength by 11.2 % and flexure strength by 27.4% when compared to the wood reference sample. and this proved that Epoxy have an effective role in strengthening wood member in both compression and flexure.
- Specimens which were supported using thin wire had their compressive and flexure strength increased by 11.35% and 11.98% respectively when compared to the wood reference sample. this proved that thin wire has a positive effect in strengthening of wood member in compression and flexure.
- Specimens which were supported using rolled wire gave higher compressive and flexure strength by 20.14% and 36.44% than the wood reference sample, and this proved that rolled wire have an effect in strengthening of wood member in compression and flexure.
- Specimens which were supported using steel mesh had both their compressive and flexure strength increased by 44.4% and 51.63% more than the wood reference sample. this proved that, steel mesh has improved the wood member strength in compression and flexure. This happened because there is a confinement between steel mesh and wooden specimen in two directions.
- The study provides positive indication regarding further application of wood, epoxy and steel as base for integration of these material in concrete application under axial and flexural loads, tenting to finally reach a fully effect timber concrete composite TCC which has

great potential in replacement of steel reinforcement.

8 References

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