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SHEAR ASSESSMENT OF FAILED RC BEAMS RETROFITTED BY SISAL MAT POLYMER COMPOSITE

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ABSTRACT: Retrofitting deteriorate structures in order to maintain and enhance the load-carrying capacity to upgrade structural components is necessary and has several economic and environmental advantages over demolition and reconstruction. The used of locally available materials, allowing the use of local skills, benefitting to the local economy and being low in cost for retrofitting should have greater priority for researchers in the field of structural engineering. In this paper, the assessment of failed RC beams retrofitted by sisal mat polymer composite externally bonded by strips on critical regions (SCR) is presented. Sisal fiber is one of the most available natural fibers and the eastern part of Africa is one of the biggest producers, so the application of sisal polymer composite as structural retrofitting needs to be investigated. The study focuses on a shear assessment where four beams were tested in three-point bending with two retrofitted after cracking and two as control specimens. By using strips in critical regions through main cracks, it was found that the sisal mat composite is suitable as raw material and increases the load-carrying capacity, reduce cracks propagation and modify the failure mode from pure shear to more ductile flexural-shear.

Keywords: Sisal mat polymer composite, Shear retrofitting, Failed beams, Strips on critical regions;

1. INTRODUCTION

Rehabilitation and retrofitting of deteriorated RC structures are major challenges for structural engineers. Structures or structural components may be subjected to various kinds of deteriorating processes: mechanical, chemical and other types of degenerating action, raising doubts about its current safety or functionality. Those deteriorations might be due to age, poor maintenance, and corrosion due to poor environmental conditions, poor initial design or construction and accidental situations (earthquakes...) [1]. There may also be changes in its requirements and practical applications, resulting in a need to raise the load-carrying capacity.

Complete demolition and reconstruction is not a wise decision and requires considerable time and money. Rehabilitation and retrofitting is an alternative solution. An appropriate maintenance, repairing or upgrading, at an appropriate time, can ensure that structures remain safe, durable and aesthetic. Over the years several techniques have been used. Concrete and steel jacketing, are some of them, despite the fact that they increase the strength, they take up space, increase the self-weight of structures, take a lot of time and labor to implement and its highly corrosive [2]. To avoid that, new technology for rehabilitation and retrofitting has been developed from polymers reinforced with artificial fibers to make a composite material. Composites comprise several different basic components that together provide physical and mechanical characteristics superior to what each can provide separately. These composites combine the strength of fibers with the stability of the polymers. They are defined as polymer matrix that is reinforced with fibers or other reinforcing material with a sufficient aspect ratio (length to thickness) to provide a desirable reinforcing function in one or more directions [3]. Fibers reinforced polymers (FRPs) are one of the most preferred materials for structural retrofitting or rehabilitation components like beams, columns or slabs. They also greatly increase ductility and energy absorption capabilities in these building components [4].

Since the nineties, a lot of studies have been done in the area of rehabilitating or retrofitting reinforced concrete structures subjected to bending, shear or axial loads using FRPs, but all these studies focused on artificial fibers such as carbon fiber (CFRP), glass fiber (GFRP) and aramid fiber (AFRP) [5]. With the world moving ahead for finding a suitable replacement of artificial fibers, with materials which should not harm and pollute the environment, materials that are locally available, accessible to the ordinary people and being low in cost, researchers investigate the production of natural fiber reinforced composites for the development of low cost polymeric reinforced composites which are entirely green and being able to improve the strength of the structure by using FRPs as the raw material like sisal, jute, hemp, flax etc. ([6]-[7]-[8]).

Sisal fiber is one of the most widely available and used natural fibers. In recent years, there has been an increasing interest in finding new applications for sisal-fiber-reinforced composites that are traditionally used for making ropes, mats, carpets, mattresses, and handcrafted articles. The properties of sisal fiber itself, the interface between sisal fiber and matrix, properties of sisal-fiber-reinforced composites and their hybrid composites have been investigated in many research and a major study on sisal fibers carried out on the used in sisal-fiber-reinforced composites including thermos-plastics, thermosets, rubber, gypsum and cement ([9]-[10]). The sisal fibers can be adapted to different processes of composites preparation, such as rolling up of filaments, lamination, and molding for resin transfers. These processes make the material strategically important in the development of bio-composites and their application as a replacement for synthetic resins fibers is an immense interest ([11]-[12]).

Many experimental investigations and theoretical analyses have been carried out to explore the strengthening of RC beams in shear with externally bonded FRP using artificial fibers and sisal fiber. Li & Leung [13] studied the shear strengthening by emphasizing on the shear ratio and its effects on retrofitted structures and it lacks accountability in the designs code for predicting the FRP contribution. They concluded that the FRP strips are most effective for medium shear span/depth ratios (1.5 to 2.5). Harishankar [14] did a comparative study of the shear behavior and ductility property of beams retrofitted by glass and sisal fiber with cement matrix composite and epoxy binder in which, ten shear deficient beams were cast, out of which eight beams were retrofitted by side bonding and two as a control. It was found that the beams retrofitted using glass fiber was showing better load carrying capacity than the beams retrofitted using sisal fibers and the Epoxy binder is more effective compared to Cement matrix composite. Sen & Reddy [15] investigated the thermal conditioning of woven sisal fiber and the efficacy of woven sisal fiber reinforced polymer composite for shear strengthening of RC beams using full and strip wrap techniques. Test results showed that strengthened beams underwent very ductile nature of the failure, without any delamination or de-bonding of sisal FRP, and also increased the shear strength and the first crack load of the reinforced concrete beams.

This paper presents the experimental result of a failed RC beam retrofitted by sisal mat polymer composite in shear. The main objective is to assess the shear behavior on maximum strength and failure mode on specimens wrapped by FRP with strips on critical regions (SCR) where only the weak and deficient part are retrofitted.

2. MECHANICAL PROPERTIES OF THE SISAL MAT AND SISAL MAT COMPOSITE

The sisal mat has been obtained locally in the eastern part of Kenya, through a village cooperative in Matiniyani (Kitui), where the local farmers produce sisal fibers and make by hand weaving and traditional weaving equipment (Fig.1) divers subject like the floor sisal mat which was used for the retrofitting in this experimental study. The floor mat is a plain sisal mat weaved by yarns made from the harvest sisal fibers to make a fabric which can be suitable for many purposes. Also, the epoxy matrix was used as adhesive for the retrofitting which can provide good resistance to corrosion, low weight, and high strength.

2.1 Sisal Mat Composite Fabrication

For the composite fabrication, a unidirectional sisal mat fabric has been used. To process the composite, the hand lay-up technique was used for the preparation of the samples and fabrication of the composite. The epoxy resin used for the impregnation is Sikadur-330 obtained from Sika group made up of two pre-dosed components, the thixotropic epoxy based impregnating resin and adhesives. Table.1 gives the mechanical properties of the epoxy according to the manufacturer.

After all, specimens were cut with equal size according to ISO 527-1with a testing length of 200mm, a calculated amount of Part A = epoxy resin and Part B= hardener, with a 4:1 ratio, have been mixed together with an electric drill before use. Once the matrix has acquired excellent properties, a particular formwork made especially for the sisal mat plate composite with the thickness of 5 mm and width of 50 mm was used as a mold. In order to ensure a good distribution of the matrix and avoid air bubbles, a constant pressure was applied from the top of the mold during 24 hours after which the sisal mat composite was removed from the mold and cured during 7 days in an ambient environment before the mechanical testing.

Table1: Mechanical Properties of Sikadur-330**.**

Modulus of Elasticity in Flexure	~3800 N/mm^2 (7 days at +23°C)	(DIN EN 1465)
Tensile Strength	~30 N/mm^2 (7 days at +23°C)	(ISO 527)
Modulus of Elasticity in Tension	~4500 N/mm^2 (7 days at +23°C)	(ISO 527)
Elongation at Break	0.9 % (7 days at +23°C)	(ISO 527)
Tensile Adhesive Strength	Concrete fracture ($> 4N/mm^2$) on the sandblasted substrate	(EN ISO 4624)
Coefficient of Thermal Expansion	4 x 10^{-5} 1/K (Temperature range -10°C - +40°C)	(EN 1770)

1.1 Mechanical Testing

To investigate the mechanical properties of sisal mat and sisal mat composites, a tensile test was performed for all specimens. For the sisal mat, a sample of 10 specimens(Fig.2) was investigated according to ISO 13934-1(1999) using UTM (Universal Testing Machine) with a testing speed of 20mm/min on the natural untreated sisal mat cut following the warp (90°) direction. The tensile test was carried out by applying uniaxial load through both the ends of the specimen, using suitable jaws as an attachment (Fig.3).

As the sisal mat, six specimens of the sisal mat composite were also tested after the curing in tensile according to ISO 527-5:2009. All tensile tests were conducted in a normal atmosphere on specimens by means of a universal testing machine under displacement control of the crossbar by a high-precision extensometer. Only five specimens failed properly according to the requirement of the standard why only those results were taken account (Fig.4).

All results were taken as an average value of specimens tested in each sample, for the sisal mat and the sisal mat composite. The experimental results achieved from tensile tests on the sisal mat cut at warp direction, have shown a good behavior despite most of the specimens failed at jaws but none of those values was bigger than those failed at the middle of the specimens. The values of the mechanical characteristics obtained are peak tensile strength, the elasticity modulus, and the elongation. The Poisson ratio for the sisal mat composite was obtained by monitoring the longitudinal and transversal strains using strain gauges' type of UBFLA-1mm through a DATA LOGGER TDS-630. Results are summarised in Table 2. Fig. 5 gives the stress-strain diagram for all specimens of the sisal mat composite.

Fig. 1 Sisal mat weaving

Fig. 2 Sample specimens warp direction

Fig. 3 Specimens warp direction Testing (UTM)

Fig. 4 Specimens of Sisal Mat Composite after testing

Table.2 : Mechanical Properties of Sisal Mat and Sisal Mat Composite

Sisal Mat	Tensile Strength f_t (MPa)	Elongation at Rupture (%)	Tensile Modulus E (GPa)	Density (g/cm^3)	Poisson Ratio
Warp direction	55.446	4.91	-	-	-
Sisal Mat Composite	46.035	0.66	7.9694	0.7795	0.34

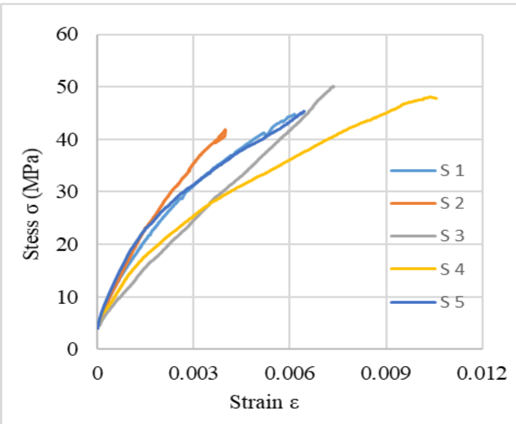

Fig. 5 Stress-Strain Sisal Mat Composite

3. MATERIALS

3.1 Concrete

The ordinary normal concrete designed according to ACI 211.1-91 for a concrete grade M25 using an Ordinary Portland Cement Type I (CEM I 42.5 N) called “Bamburi Power Plus”. It is made locally in Kenya, by the manufacturer “Bamburi Cement Ltd Company”. For aggregates, the conventional (gravel and sand) has been used for this experiment with a nominal size of 4.76mm for the ordinary river sand in which the basic properties were checked (specific gravity, water absorption, and particles distribution). For the coarse aggregate as the fine, a nominal size of 20mm locally obtained were used, in which also, the specific gravity, water absorption, and bulk density have been determined according to AASTO T85 and ASTM C127. The design results a mix proportion by weight of cement/sand/gravel was found to be 1:1.625:2.907 with a water-cement ratio of 0.5. To check the compressive strength and determine Young's modulus and Poisson ratio, three cubes, and two cylinders were cast using the stated mix proportion and water-cement ratio, and the average compressive strength after the curing 28 days in normal water were found 27.742 MPa with a Poisson ration of 0.22 obtained through the DATA LOGGER by using strain gauges’ PL-60 on a concrete cylinder of 75X150 cross-section with Young's modulus of 23.653 GPa.

3.2 Steel

The conventional steel used was the TMT (Thermo-Mechanically Treated) re-bars in diameters 12, 10 and round 6 in which a tensile test has been carried out according to ASTM A370 using a UMT with an extensometer to determine the mechanical behavior. The maximum strength and the yielding point are (637.395 *N/mm*^{2} with 5390890 for diameter 12; 594.407 *N/mm*^{2} with 499.630 *N/mm*^{2} for the diameters 10 and 432.425 *N/mm*^{2} with 412.675 *N/mm*^{2} for diameter 6) with a Young's modulus of 200 GPa obtained through the diagram stress-strain (Fig.6).

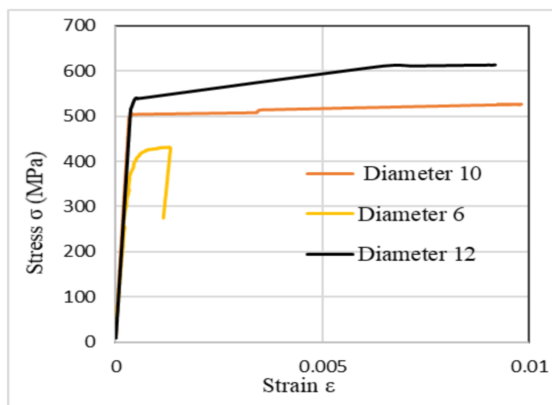

Fig. 6 Stress-Strain Re-bars

4. EXPERIMENTAL PROGRAM

The experimental program was performed to assess the shear capacity and the behavior of failed RC beams retrofitted by sisal mat composite using strips of critical region (SCR) under monotonic loading independence of the shear length ratio. During the test, crack pattern by visual examination and strain were monitored using appropriate gauges on the side of every beam for concrete and steel bars.

4.1 Tested Specimens

Four beams in two samples were tested. All beams used in this work were 1100 mm length with a rectangular cross section of 150 x 200 mm. Longitudinal reinforcement in tension and compression was provided by three steel bars in the bottom and two on the top with nominal diameters of 10 mm as shown in (Fig.7.a) for sample one. Two beams (S1-C and S1-R). S1-C is the control specimen and S1-R is the retrofitted one. The shear ratio for the first specimen (span-to-depth) is $a_v/d=2.25$.

For sample two, two beams S2-C and S2-R have also been tested with the same length and the same cross-section. The longitudinal reinforcement in tension and compression was provided by three steel bars in the bottom and two on the top with nominal diameters of 12. The shear ratio is about $a_v/d=1.5$ as shown in (Fig.7.c). According to the so-called "Kani's Valley of Shear Failures, shear failure occurs for values of the shear ratio of 2.5 and 1.5).

A concrete cover of 25 mm was provided for all samples in all sides of concrete beams. The strain gauges used for steel bars were PFL-30 and for concrete PL-60 provided by TML.

Table 3: Experimental Coding of Specimens

Specimens	Group	a_v/d ratio	Sisal Mat Polymer Composite		Pre-cracking Load (kN)	
			Width mm	Spacing mm	Max. Load from design	Max. load during cracking
Sample One	S1-C	2.25	-	-	104.75	-
	S1-R		100	200	104.75	107.441
Sample two	S2-C	1.5	-	-	174.8	-
	S2-R		100	100	174.8	159.423

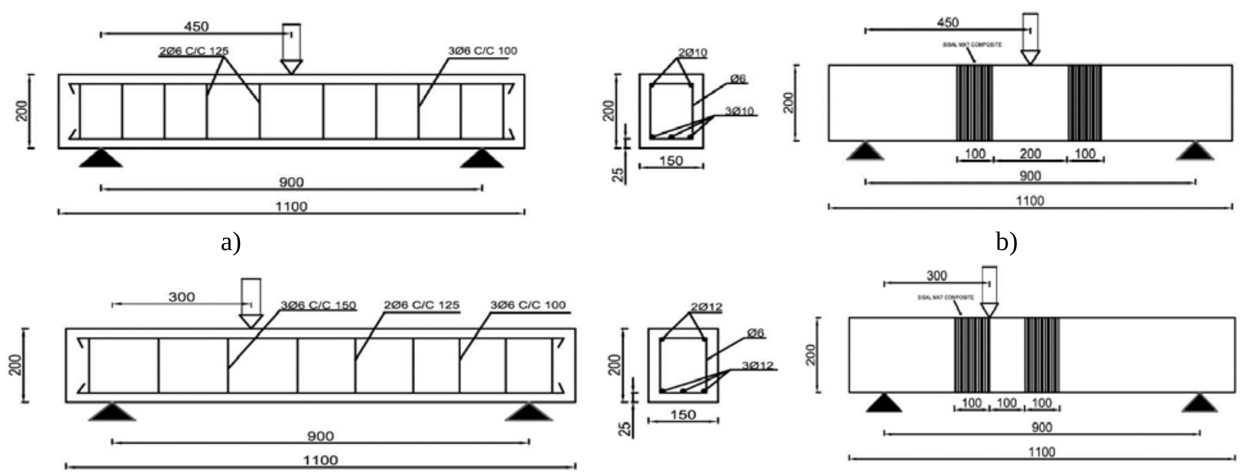

Fig. 7 Tested Specimens; a) Steel reinforcement sample one; b) Retrofitting conFiguration sample one; c) Steel reinforcement sample two; d) Retrofitting conFiguration sample two;

4.2 Test Set up and Procedure

All of the beams were submitted to three-point bending. The tests were conducted on all specimens to determine their load capacity, mode of failure and the suitability of sisal mat composite (natural untreated) as upgrading structural beams under shear failure.

Two beams were pre-cracked up to maximum load before retrofitting by loading them beyond the cracking point (Table 3) to simulate the condition of a typical structural failure prior to repair by mortar and retrofit them (S1-R and S2-R) within main cracks by strips on critical regions (Fig.7. b, d). After repairing cracks with mortar and let cure for 24 hours, the concrete surface was cleaned with sandpaper by grinding to remove dust or debris and fine particles (Fig.8.c). Then, the epoxy and hardener was mixed according to the supplier's instructions and applied to the concrete surface and on the sisal mat sheet (Fig.8.d) for a primer curing (around 15 min after application), after which the sisal mat sheet was placed in position on the concrete surface and pressed using a hand-paint roller until the epoxy was forced out on both sides (around 10 min) (Fig.8.e). To ensure a good bond with the concrete, an additional line of epoxy was applied along the edges and on the length of the retrofitted surface (Fig.8.f). The application of the epoxy and the retrofitting were conducted at the material and structural lab at temperature around 23 °C. After 7 days of curing in an ambient environment at the same conditions, the retrofitted elements were tested up to rupture under static loading using a hydraulic jack associated with a load cell. In addition to the strain gauges (SG), the load-point deflection was measured using linear voltage differential transducers (LVDTs) and visual examination on the surface for cracks pattern and type of failure were carefully observed and recorded.


a)


b)


c)


d)


e)


f)

Fig. 8: a) Sample S1-R pre-cracking; b); c) Surface cleaning; d) Epoxy lining on substrate and sisal; e) Sisal composite applying; f) Applying protecting epoxy line;

5. RESULT AND DISCUSSION

All tests results are summarizing in table 4 in terms, ultimate loads and maximum deflection at loading point where all specimens were tested for ultimate strength to get the mechanical behavior of the retrofitted cracks beams through failure mode (peeling, composite mat rupture or concrete crushing) at breaking load and suitability of using the sisal mat composite as row material by only enhancing elements through main cracks. It was observed that the initial stiffness of the retrofitted element on sample two (S2-R) and the control beam are similar before first cracks but after the S2-R became a little lower for the post-cracking up to the maximum load and the retrofitted element was more ductile with a bigger carrying capacity in term of ultimate strength as shown in (Fig.11). This behavior can be explained by the conFiguration of the upgrading, where one of the strips of the sisal composite is directly under the loading point which restraint the cracks pattern and growth so the rigidity lost by the reinforced concrete during the pre-cracking was compensated with the composite material by increasing slightly the failure load.

For elements on sample one, it was observed a similar behavior for the control and the failed retrofitted element in term of rigidity. The S1-R shown a lower stiffness with a bigger carrying capacity for maximum strength accompanied by a huge ductility (Fig.10). As sample two, the upgrading conFiguration is the main reason for this behavior by placing the composite sheets at 10 cm from the loading point around the middle of mains cracks made the mid-span more ductile.

Table 4: Test Results

Specimens	Group	Ultimate Loads (kN)	Deflection at Load Point (mm)	Retrofitting effect ratio %
Sample 1	S1-C	109.381	23.2006	-
	S1-R	132.462	46.476	21.1%
Sample 2	S2-C	160.961	18.948	-
	S2-R	168.788	21.335	4.87%

Regardless that, the retrofitted element displayed a good mechanical behavior in term of maximum strength and mode of failure. Which is demonstrated by the response of the tensile steel bars (Fig.12) with le loads-strain curves indicate a complete yielding around 120 kN. As shown following the result obtained, the enhancement of the ultimate strength is largely depending on the sisal mat composite in the soffit part of the beam apart from taking the essential shear strength.

In sample two, the sisal mat composite was more effective for the overall stiffness as shown by the steel response in (Fig13) where we can see the longitudinal reinforcement start developing a linear behavior by step around 20 kN up to 120 kN. After that, the tensile steel was more plastic than elastic so from 120 kN to 160 kN the stiffness was largely depending on the sisal composite adding to that the enhancement of the ductility and the overall take of the shear strength up to the maximum load.

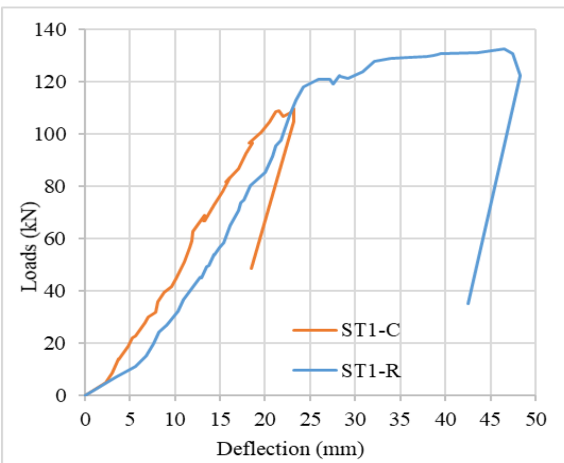

Fig. 10: Load-Deflection Sample one

For the retrofitting effect ratio, by comparing only retrofitted specimens with control it was found that sample one displayed an enhancement of 21.10% and sample two 4.78%. But knowing the retrofitted specimens were already loaded up to maximum load so structurally failed, it obvious that the enhancement is more than 100%.

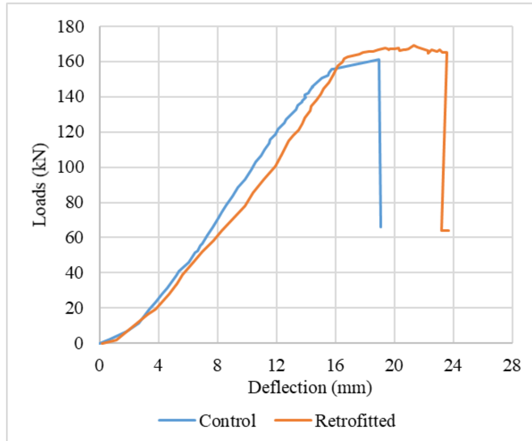

Fig. 11: Load-Deflection Sample two

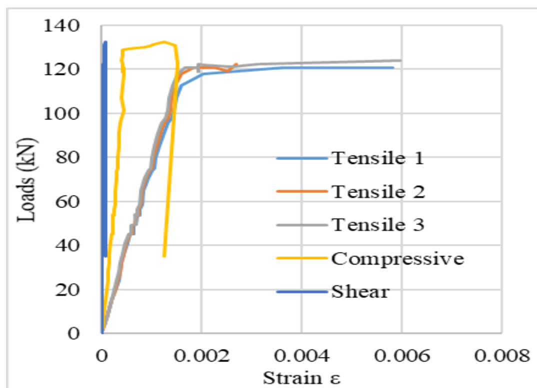

Fig. 12: Load-Strain Re-Bars Sample one

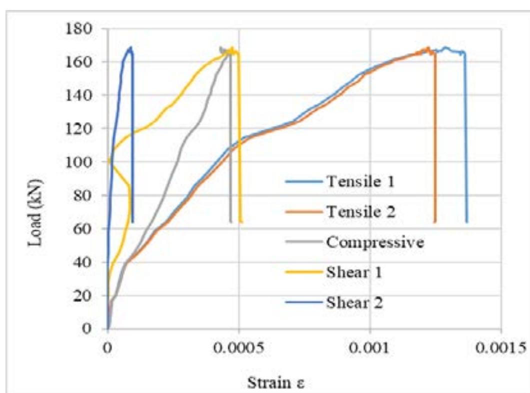

Fig. 13: Load-Strain Re-Bars Sample two

5.1 Failure Mode

All tested samples failed by steel yielding followed with concrete crushing. The main difference was the type of failure which largely depended on whether the specimens were controlled or retrofitted. For control beams, all of them failed by shear cracking at the ultimate load where the major diagonal with many fine vertical cracks appeared and developed from the lower face of the beam and then progressed towards the web side up to the loading point. After both longitudinal and vertical reinforcement yielded successively, the beams S1-C and S2-C failed suddenly by concrete crushing with the critical diagonal cracks as shown in (Fig.14. a, b).

The failure process of retrofitted specimens displayed a different cracks pattern appearances and development from control beams. Firstly, a vertical crack started at the middle between the two sisal composite under the loading point and then followed by a fine mix cracks initiated at the edge inner of the sisal composite vertically before being diagonal and progress toward the loading point. Looking at the evolution of crack patterns on retrofitted beams during loading indicated that crack propagation occurred over the small area between the sheets composite. Retrofitted beams turn the crack pattern and localized them at the central regions of the elements where cracks were also more widely spaced and shift the failure mode from shear to flexural by adding more ductility to the beams. Finally, those cracks growth widely at breaking load the specimens failed by concrete crushing in the main diagonal cracks during pre-cracking followed by peeling of the sisal composite at those parts of the beams. Apart from that, no de-bonding was occurred and either no sisal composite rupture at maximum load (Fig.14 c, d).

a) b) b) d)

Fig. 14: Failure mode, a) sample one S1-C; b) sample two S2-C; c) sample one S1-R; d) sample two S2-R;

6. CONCLUSIONS

The main objective of this study was to assess the mechanical properties of a damaged reinforced concrete beam retrofitted by sisal mat polymer composite. Test result indicates that:

1. The gain in shear capacity and the overall strength is very significant despite that only the weak and deficient part of specimen's trough main cracks were a strength;
2. The load-deflection graphs indicate a better behavior for retrofitted specimens in term of ultimate loads and being more much ductile;
3. The mode of failure of retrofitted specimens shift from shear rupture to flexural-shear failure with no de-bonding effect;
4. The retrofitting effect was clearly observed either for increasing the load carrying capacity, changing the cracks pattern and the reduction of cracks propagation;
5. The locally natural untreated sisal mat weaved by hand are suitable as raw material for structural retrofitting;

7. ACKNOWLEDGMENTS

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