



Research Article

Analytical and experimental study on shear performance of RCC beam elements reinforced with PSWC rebars: a comparative study

Shoib Bashir Wani ^a , Sarvat Gull ^{b,*} , Ishfaq Amin ^c , Ayaz Mohmood ^b 

^a Department of Civil Engineering, B. S. Abdur Rahman University, Vandalur 600048, India

^b Department of Civil Engineering, National Institute of Technology, Hazratbal, Srinagar 190006, India

^c Department of Civil Engineering, Maharshi Dayanand University, Rohtak, Haryana 124001, India

ABSTRACT

Early distress in RCC (Reinforced Cement Concrete) structures in the recent times poses a major problem for the construction industry. It is found that in most of cases, distresses in reinforced concrete structures are caused by corrosion of rebar embedded in the concrete. The HYSD (High Yield Strength Deformed) rebars which are used to offer excellent strength properties is detrimental to durability due to action of ribs as stress concentrators. Nowadays, concept of PSWC rebars (plain surface with wave type configuration rebars, formerly known as C-bars/mild steel rebar with curvy profile) is emerging to have a compromise between strength and durability. This investigation assesses the flexural behaviour of RCC elements reinforced with PSWC rebars. The flexural performance of RC beams of size 1000mm x 150mm x 150mm reinforced with PSWC rebars at 4mm and 6mm deformation level was studied by conducting test as per IS 516-1959 under four point loading. The performance of PSWC bar reinforced elements are compared with beams reinforced with mild steel rebars, HYSD rebars with spiral and diamond rib configuration to assess the viability of PSWC rebars to replace conventional reinforcement. The test results are validated by numerical analysis with the help of ANSYS software. Totally 15 beams are subjected to flexure test and the performance evaluators are first crack load, deflection at first crack load, ultimate load carrying capacity, deflection at ultimate load, load-deflection behaviour, load-strain behaviour and failure pattern. It is found that PSWC rebars as reinforcement in concrete beams enhanced the ductile behaviour of beams as compared to conventional HYSD and mild steel rebar beams. The energy absorbing capacity has increased significantly for beams reinforced with PSWC rebars when compared with conventional HYSD and mild steel rebar beams. The load-deflection behaviour and failure mode of PSWC rebars reinforced concrete beams were found to be similar to that of high yield strength rebars irrespective of deformation level. The analytical investigation from ANSYS software gave good agreement with the experimental results. It is concluded that PSWC bar has the potential to replace conventional HYSD rebar. Further study needs to be done to optimize the profile level and stirrup locations; and usage with high concrete grade for effective exploitation.

ARTICLE INFO

Article history:

Received 2 May 2020

Revised 25 May 2020

Accepted 31 May 2020

Keywords:

Reinforced cement concrete
ANSYS
MS rebar
HYSD rebar
PSWC rebar
Rib configuration

1. Introduction

Reinforced concrete is a composite material in which concrete's relatively low tensile strength and ductility are counteracted by the inclusion of reinforcement having

higher tensile strength and ductility as mentioned by Meddah and Bencheikh (2009). The reinforcement used, is steel reinforcing rebar and is usually embedded passively in the concrete before it sets. For many years, it has been utilized as an economical construction material in

* Corresponding author. E-mail address: r.sarvat@gmail.com (S. Gull)

one form or another in buildings, bridges, and many other types of structures throughout the world as explained by Nanni (2003). In addition to being readily obtainable, reinforced concrete has been universally accepted because it can be moulded essentially into any shape or form, is inherently rigid, and is inherently fire-resistant as defined by Gagg (2014). In reinforced concrete, the tensile strength of steel and the compressive strength of concrete work together to allow the member to sustain the stresses over considerable spans. However, failures in concrete structures do still occur as a result of premature reinforcement corrosion as explained by Song and Saraswathy (2007).

“Durability of reinforced concrete structures is a pervasive and universal problem. Many concrete structures deteriorate prematurely, and repair and maintenance costs amount to substantial proportions of public and private sector budgets. Many researchers suggests, reasons for durability problems as poor understanding of deterioration processes, inadequate acceptance criteria of site concrete, and changes in cement properties and construction practices” as mentioned by Hobbs (2001). Durability problems cover a wide range including attack by external destructive agents (e.g. sulphates), internal material incompatibilities (e.g. alkali-aggregate reaction), and aggressive environments such as freeze-thaw etc.; Nevertheless, the greatest threat to durability of concrete structures is undoubtedly corrosion of embedded reinforcing steel, leading to cracking, staining, and spalling of the cover concrete (Neville, 1987). This in turn can lead to unserviceable structures that may be compromised in respect of safety, stability, and aesthetics.

In reinforced concrete structures, reinforcing steel provides the tensile properties that are needed in structural concrete. It prevents the failure of concrete structures which are subjected to tensile and flexural stresses due to traffic, winds, dead loads, and thermal cycling. Materials used for reinforcement are usually roughly textured to encourage the concrete to fully adhere as mentioned by Garden et al. (1998). However, when reinforcement corrodes, the formation of rust leads to a loss of bond between the steel and the concrete and subsequently delamination and spalling as explained by Goyal et al. (2018). If this is left unchecked, the integrity of the structure can be affected. It is also associated with reduction in the cross sectional area of steel which in reduces strength capacity of RC structures. Hence it is necessary to identify the causes for corrosion as early as possible and implement corrosion protection techniques to safeguard the structures. The major factors influencing corrosion process of steel reinforcement in reinforced concrete structures are pore solution of concrete, moisture, chloride content, carbon dioxide, components of concrete, concrete resistivity, thickness and defects of cover concrete and temperature as mentioned by Marcos-Mason et al. (2018). Apart from the above mentioned factors, corrosion process can also be influenced by the surface deformations on the steel reinforcement used in the reinforced concrete as explained by Zhao et al. (2011). It can be recognized that the problem of early distress due to corrosion in reinforced concrete structures came into existence after the introduction of high strength rebars

with surface deformations. These rebars can be easily identified by the presence of lugs or protrusions on their surface. Compared with plain rebars, rebars with surface deformations corroded faster. These deformed rebars with a stepped profile have space concentrators on the surfaces of projections which represents the sites of preferential formation of cracks. Presence of these projections on the surface of the rebars, are the areas with high stress concentration and consequently it creates non-uniform stress distribution, paving way for formation of anode and cathode which becomes the birth place for corrosion. These rebars with surface lugs are preferred, even though they are susceptible to corrosion because of their strength and need for limiting the anchorage or bond length or lap length. A problematic feature of these rebars is that the thin edges of the lugs, which are often damaged during the making, transportation and handling. The damaged regions lead to the creation of sites with potential differences and corrosion process commences, gradually the whole lengths of bars are covered with rust. Fig. 1(a) shows the view of new and Fig. 1(b) shows the view of corroded twisted rebar.

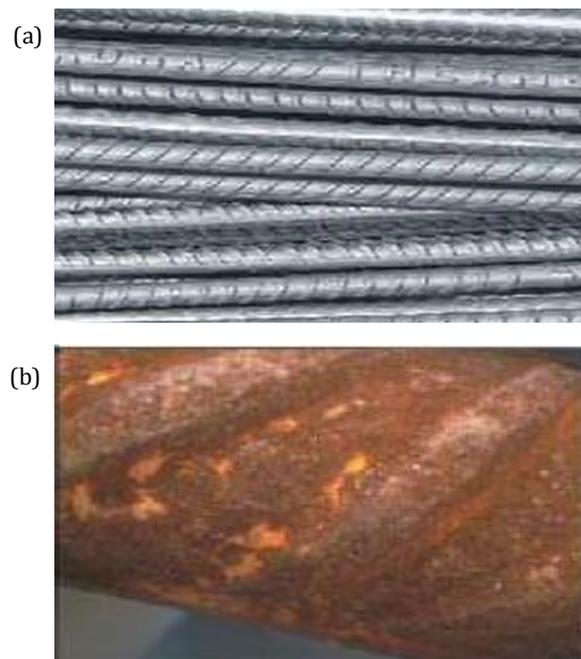


Fig. 1. (a) View of new rebars; (b) Corroded twisted rebar.

Although, the yield strength as well as the bond strength of HYSD rebars are higher as compared to those of the plain round mild steel straight rebars, there are certain durability issues related to the use of HYSD rebars in reinforced concrete structures; problems of early distress and associated failures of reinforced concrete structures, built using HYSD bars due to early corrosion of the HYSD bars, have been reported by Kar (2012). With the objective of achieving an alternative solution for overcoming the early corrosion problem in using HYSD rebars in reinforced concrete structures, a new type of reinforcing steel bar (named as PSWC rebar) with normal plain round surface having slightly curved axis has been proposed by Kar (2019). Fig. 2 shows the view of a PSWC rebar.



Fig. 2. View of a PSWC bar.

PSWC rebars are proposed with an objective of overcoming the above mentioned defects. PSWC rebar is a rebar for durable concrete construction at zero cost addition and much more. PSWC bar is characterized by its plain surface and a deformed axis to give it a gentle wave-type configuration. The offset (excursion from the original straight axis) is merely a few 4-8 millimeters. The plain surface of the PSWC rebar overcomes the problems due to corrosion because of uniform stress distribution throughout the length of the rebar. PSWC rebars can solve both, strength and durability problems. The use of PSWC rebars could possibly make the reinforced concrete structure more ductile than concrete structures which may be reinforced with conventional (with straight axis) rebars.

In this experimental study, PSWC bar with 4mm deformation and 6mm deformation are used. Fig. 3(a) shows view of PSWC rebar with 4mm and Fig. 3(b) shows view of PSWC rebar with 6mm deformation.

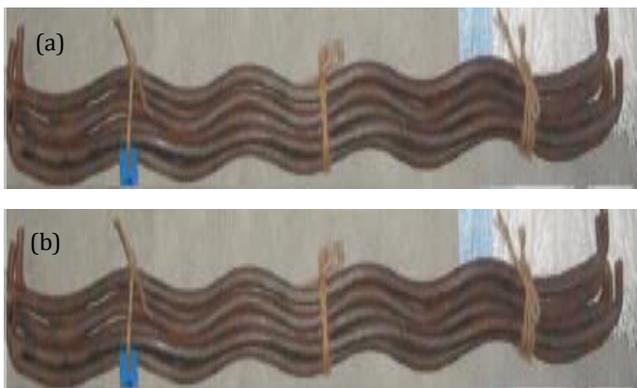


Fig. 3. (a) View of PSWC rebar with 4mm deformation; (b) View of PSWC rebar with 6mm deformation.

The scope of present investigation is to assess the flexural behaviour of RCC elements reinforced with PSWC rebars. The flexural performance of RC beams of size 1000mm x 150mm x 150mm reinforced with PSWC rebars with 4mm and 6mm deformation level is studied by conducting test as per IS:516-1959 (method of test for strength of concrete) under four point loading method. The performance of PSWC rebar reinforced elements are compared with beams reinforced with mild

steel rebars, HYSD rebars with spiral and diamond rib configuration to assess the viability of PSWC rebars to replace conventional reinforcement and subsequent use for structural application. The test results are validated by numerical analysis with the help of ANSYS software. In each category three beams are cast and totally 15 beams are subjected to flexure test. The performance evaluators in this study are first crack load, deflection at first crack load, ultimate load carrying capacity, deflection at ultimate load, load-deflection behaviour, load-strain behaviour and failure pattern. The followings are the category of RC elements subjected to flexure test:

- RC beams reinforced with mild steel bars ,
- RC beams reinforced with PSWC rebar of 4mm deformation,
- RC beams reinforced with PSWC rebar of 6mm deformation,
- RC beams reinforced with spiral rib HYSD rebars,
- RC beams reinforced with diamond rib HYSD rebars.

2. Material Properties and Mix Design

PSWC bars with 4mm and 6mm deformation level were supplied by M/S. Engineering Consultants, Calcutta. All other materials were procured locally and used. Ordinary Portland cement (OPC) – 53 grade, river sand, single graded coarse aggregate, potable water, mild steel rebars of 12 mm diameter, parallel/spiral rib HYSD rebars of 12 mm diameter, diamond rib HYSD rebars of 8 mm, 10 mm, 12 mm diameter, PSWC rebar of 10 mm and 12 mm diameter with 4 mm deformation, PSWC rebar of 10 mm and 12 mm diameter with 6 mm deformation. The basic properties of the cement such as consistency, initial setting, final setting and specific gravity were found as per IS:4031-1989 (methods of physical test for hydraulic cement), IS:269-1989 (specific gravity of cement) and IS:516-1959 (compressive strength of cement). The properties of fine aggregate and coarse aggregate are found as per IS:2386 (methods of test for aggregate for concrete). The grading is conforming to IS:2720 (part IV) – 1985. Table 1 shows the property of cement, fine aggregates and coarse aggregates.

Based on the material property test results, mix design for M25 concrete was formulated for 1m³ of concrete as per IS:10262-2009 as shown in Table 2.

Slump test was conducted to measure the consistency of concrete. Trial mix was made for determining the slump for the formulated design mix ratio. The trial mix for M25 grade of concrete was made with 63.5% of coarse aggregate and 36.5% of fine aggregate which offers a slump of 80 mm, which is found to be optimum for hand mixing.

Each rebar of 12 mm and 10 mm size of mild steel of grade $f_y = 250$ MPa, HYSD parallel ribs, HYSD diamond ribs of grade $f_y = 500$ MPa were tested to determine the corresponding chemical composition and also tension test was conducted using UTM to check the physical property of specimens. The chemical composition and tension test results were found in optimum range as shown in Tables 3 and 4 respectively.

Table 1. Material properties of cement, fine aggregate and coarse aggregate.

S. No.	Constituent	Properties/Obtained Value	BIS Recommended Range
1	Cement	Specific gravity –3.15 Consistency –32%	> 3.15
2	Coarse Aggregate	Specific gravity–2.797 Waterabsorption–0.25% Grading conforming to IS:2386-1963	2.4-2.6 -
3	Fine Aggregate	Fineness modulus-3.15 Specific gravity–2.547 Waterabsorption-6% Conforming to Zone -I Grading conforming to IS:383-1970	2.9-3.2 2.4-2.6 - -

Table 2. Design mix proportions for 1m³ of concrete.

Water	Cement	Fine Aggregate	Coarse Aggregate
153	340	695	1280
0.45	1	2.04	3.76

Table 3. Chemical composition test results.

Characteristic Test	MS rebar results	HYSD rebar results (Parallel ribs)	HYSD rebar results (diamond ribs)
Carbon (%)	0.284	0.203	0.222
Manganese (%)	0.553	0.696	0.567
Silicon (%)	0.157	0.208	0.104
Sulphur (%)	0.028	0.024	0.024
Phosphorous (%)	0.036	0.033	0.032
Chromium (%)	0.190	0.092	0.186
Nickel (%)	0.099	0.068	0.069
Molybdenum (%)	0.017	0.013	0.016

Table 4. Tension test results.

Type of bar	Properties			
	Yield strength (MPa)	Ultimate strength (MPa)	% Elongation	% Reduction
Mild Steel	466.72	583.40	27.5	54.23
HYSD Parallel Ribs	498.36	622.96	22.5	55.45
HYSD Diamond Ribs	547.77	684.72	26.2	54.90

3. Experimental Program

Concrete is relatively strong in compression and weak in tension. In reinforced concrete members, only partial amount of tensile stresses are resisted by concrete, rest of the whole tensile stresses are resisted by steel reinforcing bars. However, tensile stresses are developed in the concrete due to drying shrinkage, rusting of steel reinforcement, temperature gradients, etc. Therefore, the knowledge of tensile strength of concrete is essential.

The tensile strength of concrete cannot be measured directly; hence beams are tested for flexural strength property of concrete. Flexural strength test is carried out according to IS:516-1959. The code specifies two-point loading for measuring flexural strength of concrete.

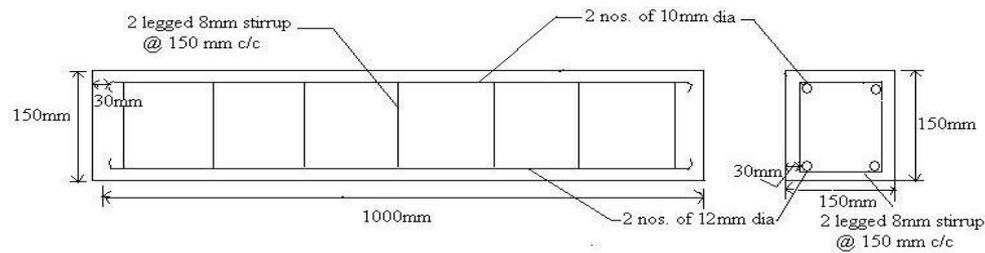
Different types of rebars were used as reinforcement and comparisons were made with PSWC rebars of 4mm and 6mm deformation. The different types of rebars used in the beam specimens are listed below in the Table 5.

Table 5. Different types of rebars used as reinforcement.

S. No.	Type of reinforcement
1	Mild steel rebars
2	High yield strength rebars with spiral rib configuration
3	High yield strength rebars with diamond rib configuration
4	PSWC rebar with 4mm deformation
5	PSWC rebar with 6mm deformation

3.1. Specimen details

The specimens were cast to a size of 150mm wide, 150mm deep and length of 1000mm. The clear cover of the beam was provided as 30mm. The bottom reinforcement was two nos. of 12mm diameter and the top reinforcement was two nos. of 10mm diameter. Two legged vertical stirrups were provided at a spacing of 150mm center to center for conventional rebars and 105mm center to center for PSWC rebars. Reinforcement details of the specimen are shown in Fig. 4 and details for different types of beams are listed in the Table 6.

**Fig. 4.** Reinforcement details.**Table 6.** Reinforcement details for different types of beams.

S. No.	Type of reinforcement	A_{sc}	A_{st}	A_{sv}	No. of specimen
1	Mild steel rebars	2 nos. of 10mm Φ	2 nos. of 12mm Φ	2 legged 8mm stirrups @150mm c/c	3
2	Spiral rib HYSD rebars	2 nos. of 10mm Φ	2 nos. of 12mm Φ	2 legged 8mm stirrups @150mm c/c	3
3	Diamond rib HYSD rebars	2 nos. of 10mm Φ	2 nos. of 12mm Φ	2 legged 8mm stirrups @150mm c/c	3
4	PWSC-bar (4mm def.)	2 nos. of 10mm Φ	2 nos. of 12mm Φ	2 legged 8mm stirrups @105mm c/c	3
5	PWSC-bar (6mm def.)	2 nos. of 10mm Φ	2 nos. of 12mm Φ	2 legged 8mm stirrups @105mm c/c	3

Notations: A_{sc} —reinforcement in compression zone; A_{st} —reinforcement in tension zone; A_{sv} —area of stirrups; Φ —diameter of rebar.

4. Materials and Preparation

Moulds were fabricated in the strength of materials laboratory. One inch thick plywood with polymer painted for protection was used. Fig. 5 shows the picture of the fabricated moulds.

Electrical resistance type strain gauge with 5mm length and 120 ohms resistance was used. The strain gauge was located at the center of one of the longitudinal reinforcements to measure longitudinal strain. A specific procedure was followed for fixing of strain gauges and it was applied for all types of specimen before casting. Fig. 6 shows the procedure for fixing of strain gauge.

Different types of rebars were procured from various places to the laboratory and reinforcement cage was fabricated in the nearby site. The tension reinforcement, compression reinforcement and stirrups were bent according to the requirement after which the cage was fabricated. Fig. 7(a-e) shows the picture of reinforcement cage of different types of bars.

A total of 15 beams were casted i.e. three in each category. The strain gauge of 5mm gauge length and 120 ohm resistance was fixed at the centre of one of the tension reinforcements. All the beams were casted in laboratory, prior to casting the inner walls of the moulds were coated with lubricating oil to prevent adhesion with hardening concrete. The materials were given a proper hand mixing and the concrete was placed in three equal layers and was given intact compaction with tamping rod until good compaction was obtained. All the beams were de-moulded after 24 hours. The beams were water cured with jute bags for a period of 28 days after casting.

The tests were carried out in Universal testing machine with 100 tonnes capacity. The bed of the testing machine was provided with two steel rollers, 38 mm in diameter, on which the specimen was supported, and these rollers were mounted at a distance of 600mm centre to centre. The load was applied through two similar rollers mounted at the third points of the supporting span spaced at 200mm centre to centre. The load was divided

equally between the two loading rollers which were connected by 30 mm thick plate on top. A load cell with 50 tonnes capacity was mounted on the plate fixed at the top of the rollers. A sensitive dial gauge with 0.01 mm least count was placed at the center of the beam to measure mid-span deflection. A strain gauge length of 5 mm with

120 ohm resistance was fixed at the center of bottom reinforcement, which was connected to the Universal Data Acquisition and Control System which in turn connected to the computer. The load-strain behaviour was obtained automatically from the system attached with 16 channel data logger. The test setup for flexure test is shown in Fig. 8.



Fig. 5. View of fabricated moulds.

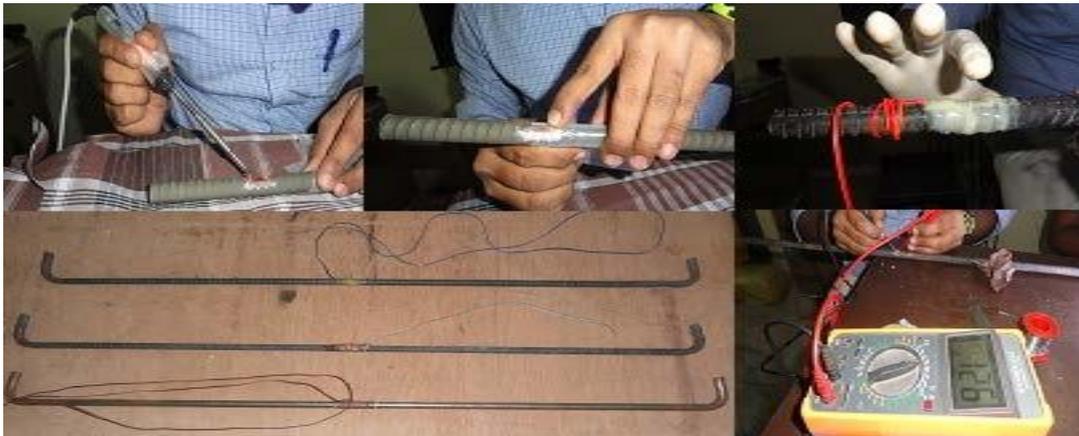


Fig. 6. Fixing of strain gauge.



(a) View of PSWC 4mm deformation reinforcement cage



(c) View of HYSD diamond rib reinforcement cage



(b) View of PSWC 6mm deformation reinforcement cage



(d) View of Mild steel reinforcement cage



(e) View of HYSD parallel rib reinforcement cage

Fig. 7. Reinforcement cage for different types of rebar.

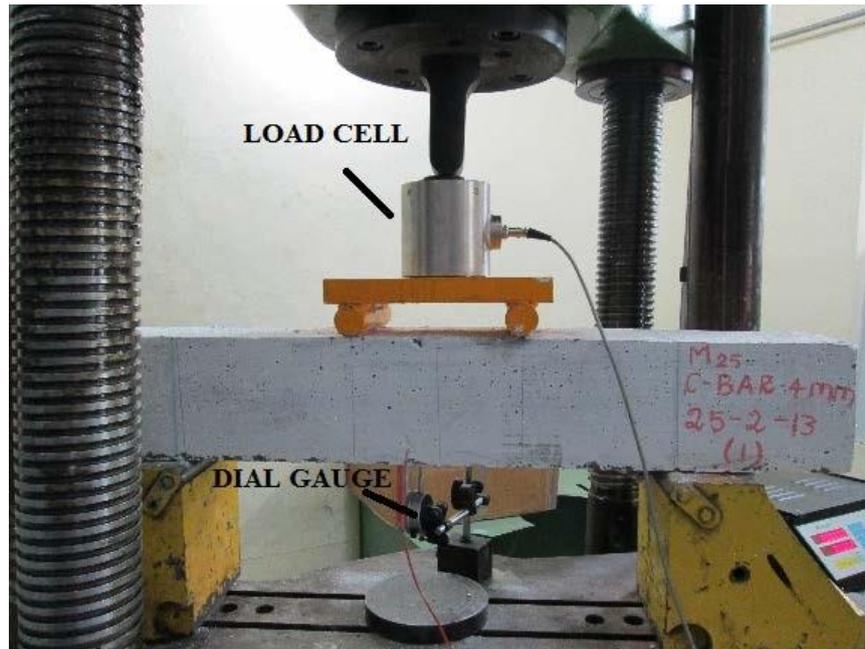


Fig. 8. Flexural strength test setup.

5. Test Procedure

The dimensions of each specimen were noted before testing. The specimens were given marking at the center, supports and along the roller axis. The bearing surfaces of the supporting and loading rollers was wiped clean, and any loose sand or other material was removed from the surfaces of the specimen where they are to make contact with the rollers. The specimen was then placed in the machine in such a manner that the load shall be applied to the uppermost surface as cast in the mould, along two lines of rollers spaced 200mm apart. The axis of the specimen was carefully aligned with the axis of the loading device. The load was applied gradually without shock and was increased until the specimen fails. The maximum load applied to the specimen during the test was recorded as ultimate load. The appearance of the fractured faces of concrete and any unusual features in the type of failure was noted.

The flexural strength of the specimen shall be expressed as the modulus of rupture f_b , which, if ' a ' equals the distance between the line of fracture and the nearer support, measured on the centre line of the tensile side of the specimen, in cm, shall be calculated to the nearest 0.5 kg/sq cm as follows:

$$f_b = p l / b d^2 \quad (1)$$

when ' a ' is greater than 20.0 cm for 15.0 cm specimen, or greater than 13.3 cm for a 10.0 cm specimen, or when ' a ' is less than 20.0 cm but greater than 17.0 cm for 15.0 cm specimen, or less than 13.3 cm but greater than 11.0 cm for a 10.0 cm specimen.

$$f_b = 3p a / b d^2 \quad (2)$$

where d is measured depth in cm of the specimen at the point of failure, l is length in cm of the span on which the specimen was supported, and p is maximum load in kg applied to the specimen.

If ' a ' is less than 17.0 cm for a 15.0 cm specimen, or less than 11.0 cm for a 10.0 cm specimen, the results of the test shall be discarded.

6. Analytical Investigation

Experimental based analysis has been widely used as a means to find out the response of individual elements of structure. This method is time consuming and the use of materials can be quite costly. In recent years, the use of finite element analysis has increased due to progressing knowledge and capabilities of computer software and hardware and has become the choice of modern engineering tools for the researcher to analyze concrete structural components.

The use of computer software to model these elements is much faster, and extremely cost-effective.

6.1. Modelling and analysis of RC beam reinforced with conventional rebars and PSWC rebars using ANSYS

Modelling of the reinforced concrete beam was done using ANSYS software. The reinforcement was modelled exactly as embedded in the concrete with sufficient cover thickness on either side. The beam was subjected to two point loading according to the Indian standards codal provisions. The analysis is made for both conventional rebars and PSWC rebars, and the results of the analysis are validated and compared with the results of the experimental investigation.

Solid65 element was used to model the concrete material, since it has capability of both cracking in tension and crushing in compression. Solid65 element has 8 nodes with three degrees of freedom at each node – translations in the nodal x , y , and z directions. Fig. 9 shows the picture of element Solid65.

The Link8 spar element was used to represent the reinforcing steel rebar. Two nodes are required for this element such that each node has three degrees of freedom, translations in the nodal x, y, and z directions. The element is also capable of plastic deformation. Fig. 10 shows the picture of element link spar 8. The beam specimens modeled in ANSYS software are shown in the Figs. 11-15.

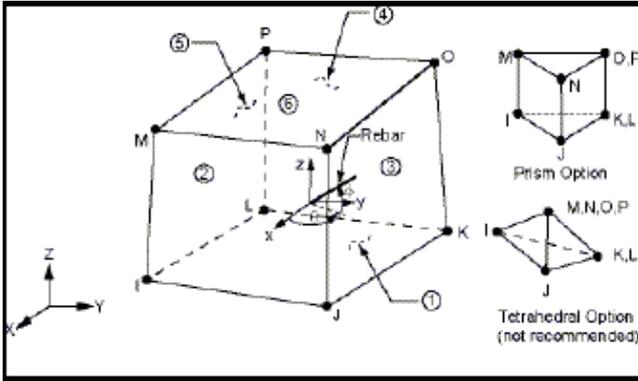


Fig. 9. Element type: Solid65.

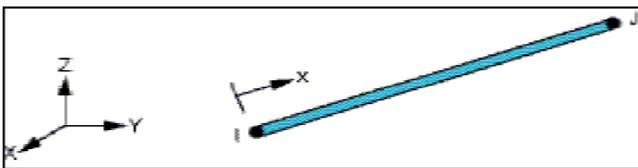


Fig. 10. Element type: Link8.

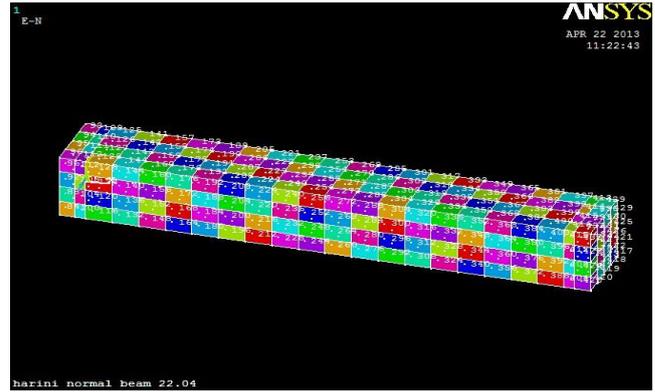


Fig. 13. Concrete block.

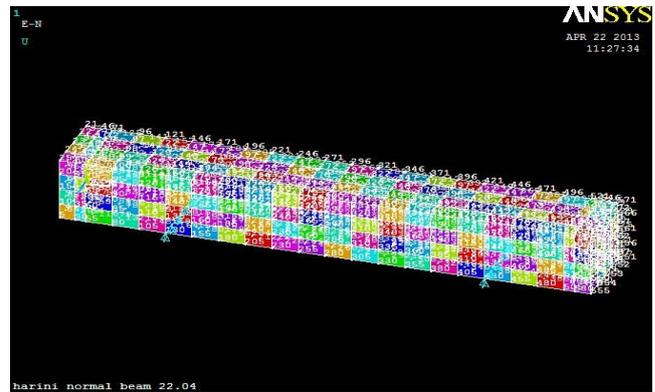


Fig. 14. Support condition.

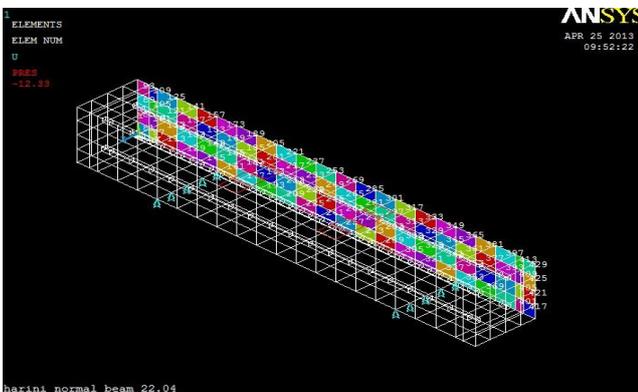


Fig. 11. Reinforcement model of conventional bar.

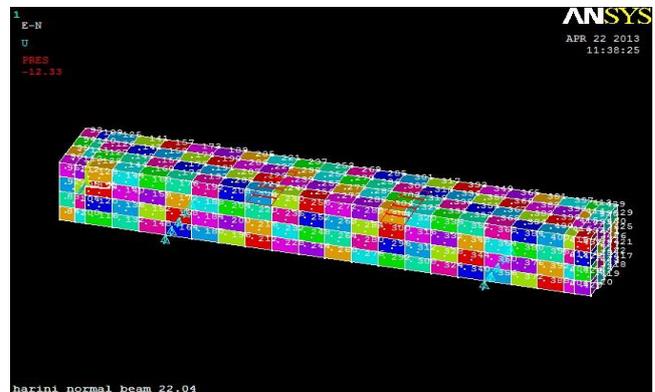


Fig. 15. Loading diagram.

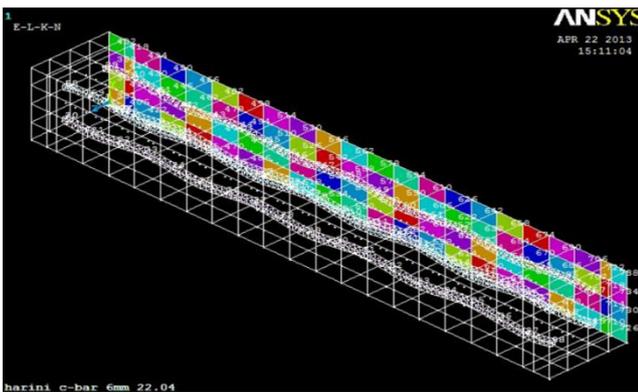


Fig. 12. Reinforcement model of PSWC bar.

7. Results and Discussion

The flexural performance of PSWC rebars was evaluated and compared with different types of rebars. A total of 15 beams of size 1000mm x 150mm x 150mm were casted and subjected to flexural test according to IS:516-1959 under four point loading. The categories of beams tested include:

- RC beam with PSWC rebar (4 mm deformation),
- RC beam with PSWC rebar (6 mm deformation),
- RC beam with mild steel rebars,
- RC beam with spiral/parallel rib HYSD rebars,
- RC beam with diamond rib HYSD rebars.

The experimental results are compared with analytical results obtained from ANSYS.

7.1. Flexural strength test

The beam specimens were subjected to four-point loading as per IS:516-1959 to assess the flexural behaviour. The evaluation parameters include load-deflection behaviour, first crack load, ultimate load, load-strain behaviour & crack pattern. Table 7 exhibits the observation on flexure test with respect to load carrying capacity. It can be observed from the table, the first crack load of PSWC rebar reinforced beams are found to be in the range of 45kN-55kN which is appreciably high than that of HYSD rebar beams and mild steel rebar beams, while the ultimate load capacity of PSWC rebar reinforced concrete beams are found to be appreciably less than that of

HYSD rebar beams and mild steel rebar beams. This could be attributed due to low compressive strength of concrete and yielding nature of PSWC rebars.

The observation on ultimate load and mid-span deflection are explicit in the Table 8. It can be observed that deflection at first crack load is marginally high for beams with PSWC rebars as compared to beams with mild steel and HYSD rebars. Significant increase in deflection level for beams with PSWC rebars at ultimate load irrespective of deformation level as compared to beams with mild steel and HYSD rebars exhibiting improved ductility.

Figs. 16-20 show the load-deflection behaviour at mid-span for beams with HYSD rebars, mild steel rebars, and PSWC rebars with 4mm and 6mm deformation.

Table 7. Observation on flexure test with respect to load carrying capacity.

S. No.	Type of specimen	First crack load (kN)	Ultimate load (kN)
1	Beams with spiral rib HYSD rebars	51	165
2	Beams with diamond rib HYSD rebars	40	185
3	Beams with mild steel rebars	55	165
4	Beams with PSWC rebars (4mm deformation)	56	130
5	Beams with PSWC rebars (6mm deformation)	45	120

Table 8. Observation on ultimate load and mid-span deflection.

S. No.	Type of specimen	First crack load (kN)	Deflection at first crack (mm)	Ultimate load (kN)	Mid-span deflection (mm)
1	Beams with spiral rib HYSD rebars	51	0.35	165	4.98
2	Beams with diamond rib HYSD rebars	40	0.25	185	4.28
3	Beams with mild steel rebars	55	0.27	165	3.08
4	Beams with PSWC bars (4 mm deformation)	56	0.54	130	7.10
5	Beams with PSWC bars (6 mm deformation)	45	0.48	120	7.20

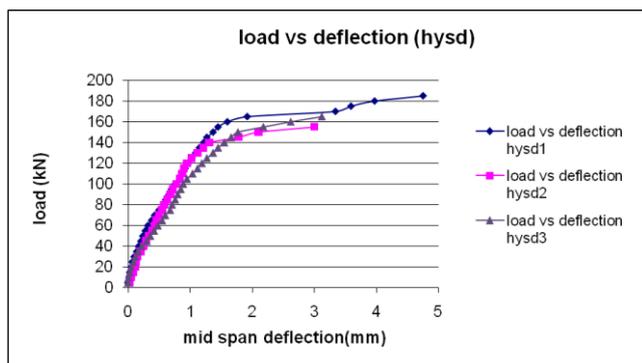


Fig. 16. Load-deflection behaviour for beams with rib HYSD rebars.

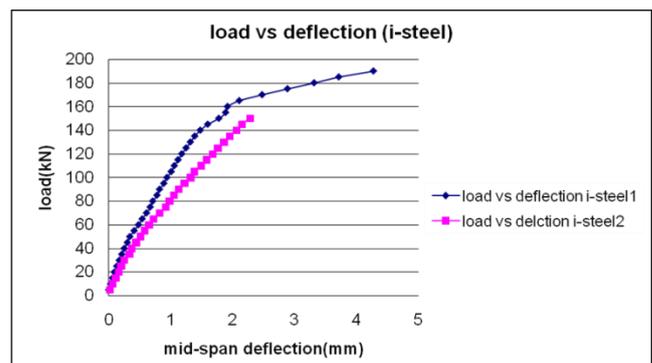


Fig. 17. Load-deflection behaviour for beams spiral with diamond rib HYSD rebars.

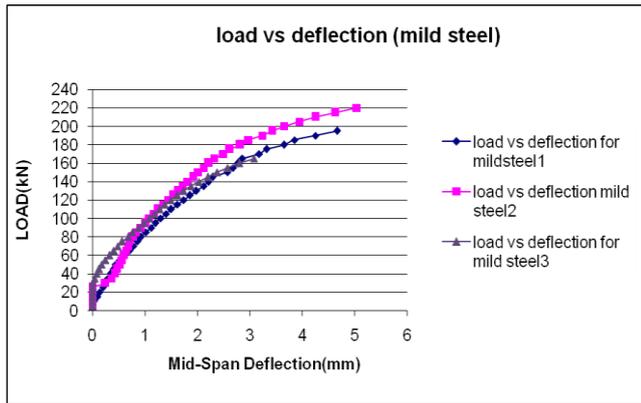


Fig. 18. Load-deflection behaviour for beams with mild steel rebars.

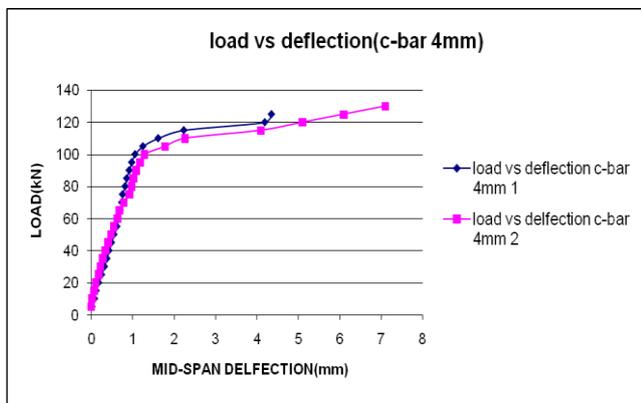


Fig. 19. Load-deflection behaviour for beams with PSWC rebar (4mm deformation).

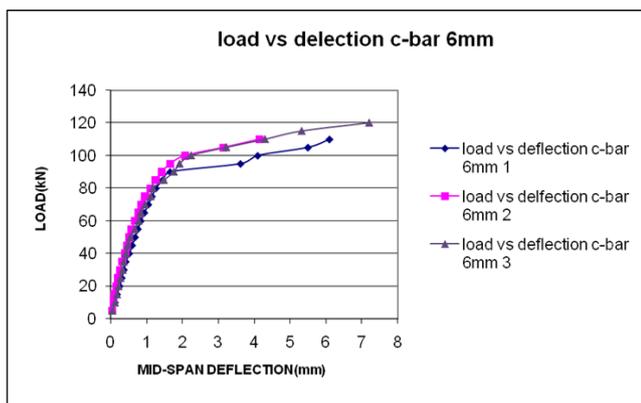


Fig. 20. Load-deflection behaviour for beams with PSWC rebars (6mm deformation).

From Figs. 16-20, it can be observed that in all the specimens, the first crack load was found to be in the range of 40 kN to 55 kN. The first crack load of PSWC rebar reinforced beams are found to be appreciably higher than that of HYSD rebar beams and the deflection recorded corresponding to those loads are higher, indicating the ductile behaviour of PSWC rebars. On further increase of load beyond first crack load, the deflection has increased rapidly upon small increase of load.

From Figs. 16 and 17, the linear behaviour exists up to a load of 140 kN for beams with spiral and diamond rib HYSD rebars. On further increase of load, appreciable deflection was recorded for small increment of load until failure. It can be seen from the Fig. 18, deflection was found to be negligible up to a load of 25 kN, and from there on it has increased gradually until the failure and almost a linear behaviour has been observed up to 180kN, which indicates, for appreciable increase of load, there is rapid increase in the deflection which registers brittle failure of beams.

Figs. 19 and 20 exhibit the Load - deflection behaviour of beams with PSWC rebar (4mm and 6mm deformation). Almost a linear behaviour exists up to a load of 100kN, upon further increase of load, softening of curve has emerged which indicates for small increase of load there is rapid increase in deflection. The deflection pattern registered before failure reveals improved ductile behaviour for beams with PSWC rebars irrespective of deformation level.

7.2. Comparison of load-deflection behaviour of beams with PSWC rebars, HYSD rebars and mild steel rebars

The load vs. deflection behaviour of PSWC rebar beams is compared with conventional HYSD rebar beams and mild steel rebar beams. The various combinations of load-deflection behaviours are plotted in Figs. 21-28.

Figs. 21-28 show the combined load vs. deflection behaviour of HYSD, mild steel and PSWC rebar reinforced beams. From Figs. 24-25, it can be seen that, the load deflection behaviour of PSWC rebar beams is found to be similar to that of other conventional rebar beams especially with spiral rib and diamond rib HYSD rebar beams. It can be observed that, large deflections are recorded for small ultimate loads for PSWC rebar reinforced beams; this could be due to the ductile behaviour of beams, which is imparted by the deformed profile of PSWC rebars. A well-defined and almost a similar load-deflection behaviour has been recorded for PSWC rebar reinforced beams, although there is marginal reduction in ultimate load when compared with HYSD and mild steel rebar reinforced beams.

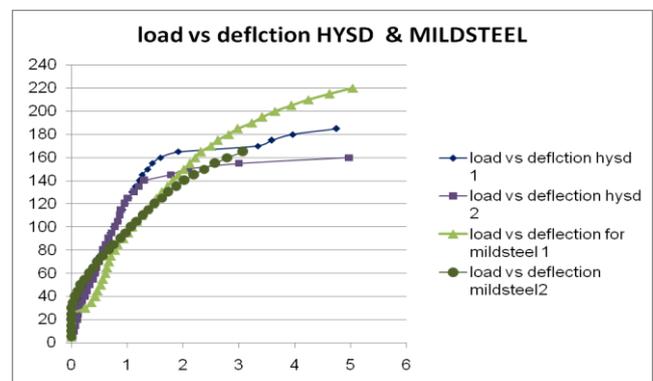


Fig. 21. Load-deflection behaviour of beams with spiral rib HYSD rebars and mild steel rebars.

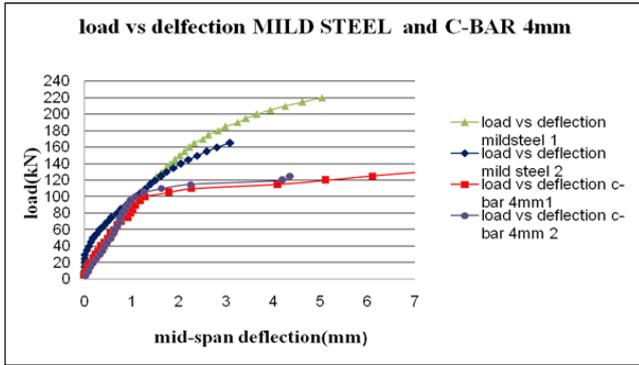


Fig. 22. Load-deflection behaviour of beams with mild steel rebars and PSWC rebars (4mm deformation).

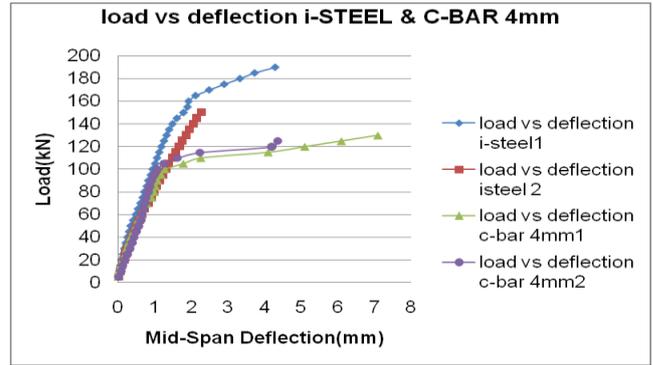


Fig. 26. Load-deflection behaviour of beams with diamond rib HYSD rebars and PSWC rebars (4mm deformation).

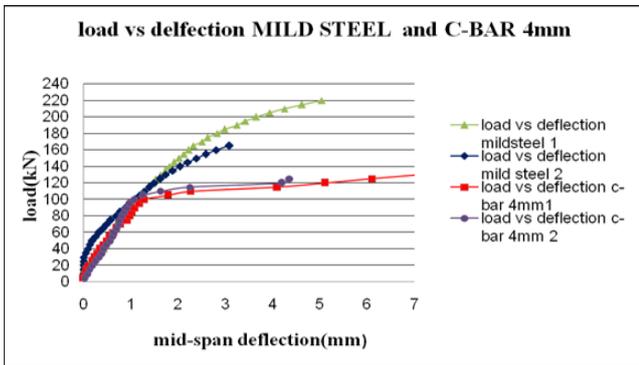


Fig. 23. Load-deflection behaviour of beams with mild steel rebars and PSWC rebars (6mm deformation).

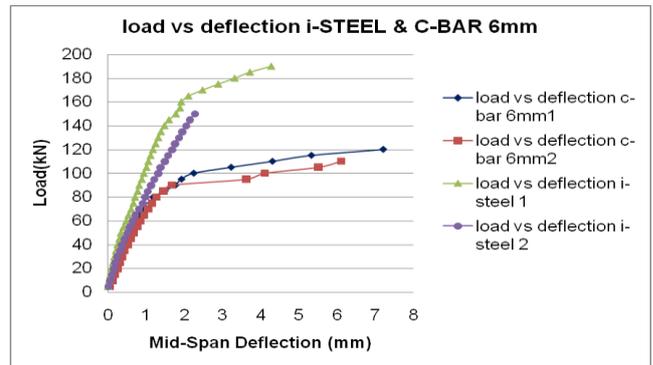


Fig. 27. Load-deflection behaviour of beams with diamond rib HYSD rebars and PSWC rebars (6mm deformation).

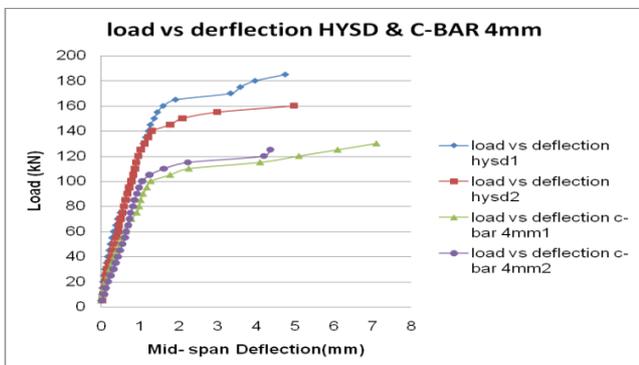


Fig. 24. Load-deflection behaviour of beams with spiral rib HYSD rebars and PSWC rebars (4mm deformation).

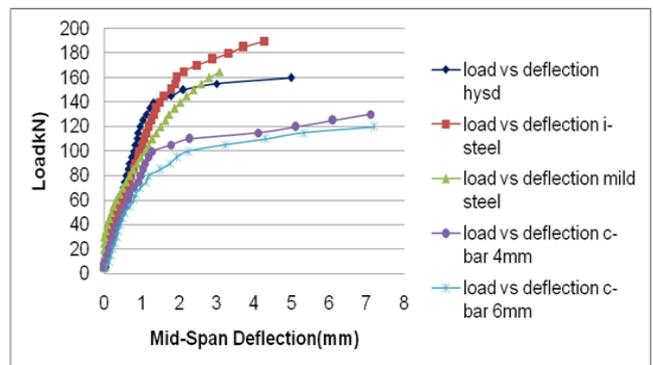


Fig. 28. Load-deflection behaviour of beams with mild steel rebars, HYSD rebars and PSWC rebars.

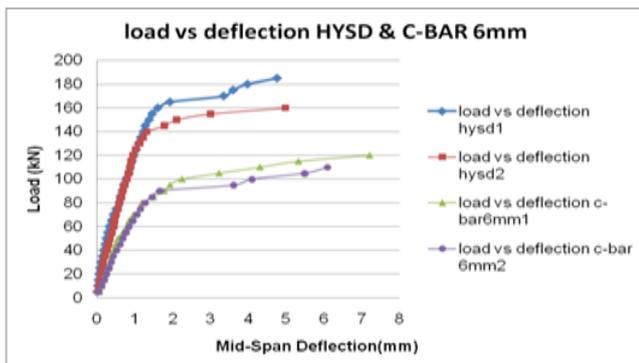


Fig. 25. Load-deflection behaviour of beams with spiral rib HYSD rebars and PSWC rebars (6mm deformation).

7.3. Load-strain behaviour

The strain gauge was fixed at the centre of the reinforcement to record load vs. strain behaviour. This was recorded automatically by the system connected to data logger, through digital data acquisition system. Fig. 29(a-c) shows the load vs. strain behaviour of beams with HYSD, mild steel and PSWC rebar, respectively. From Fig. 29(a-b), it can be inferred that in case of HYSD rebar beams, there is a gradual increase in the strain upon increase of load and yielding of reinforcements was not observed during the test. For PSWC rebar reinforced beams, the Load vs. strain behaviour of PSWC rebar with 4mm deformation is shown in the Fig. 29(c). It

is observed that strain has increased rapidly in the initial stages of load application and the yield plateau recorded shows the improved ductile behaviour of PSWC rebars. Further studies have to be carried for better understanding of load-strain behaviour of PSWC rebars.

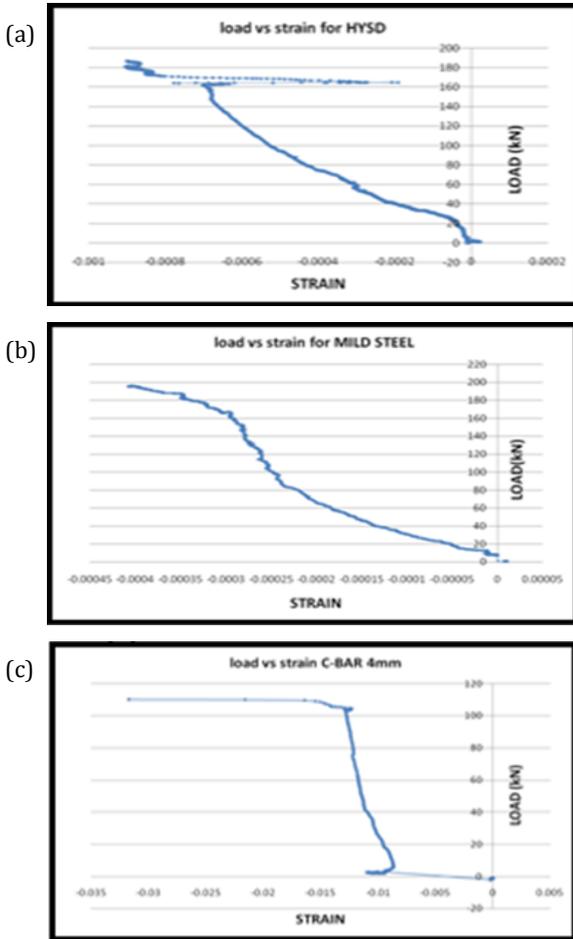
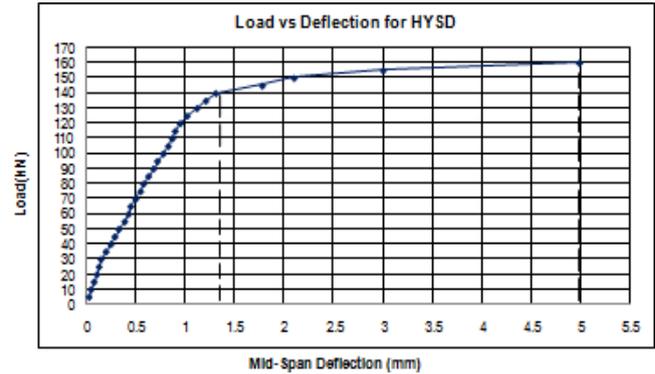


Fig. 29. Load vs. strain behaviour: (a) HYSD; (b) Mild steel; (c) PSWC rebar (4mm deformation) reinforced beams.

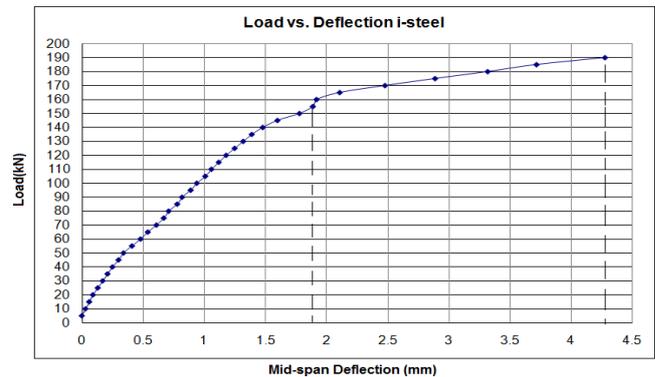
In this study, the displacement ductility was investigated. Table 9 shows the ductility and energy absorbing capacity of the HYSD rebar beams, mild steel rebar beams and C-bar beams and Fig. 30(a-d) shows the load-deflection curve with projected yield deflection and ultimate deflection for the tested beams and ductility calculations. It can be observed from the Fig. 30(a-d) that, the ductility has immensely increased for beams reinforced with C-bars than beams reinforced with HYSD rebars and mild steel rebars. It is registered from the curves of above figures that C-bar reinforced beams had a significant increase in energy absorbing capacity. This could be due to the large deflection recorded for small increment of load in the post peak region.

7.4. Failure mode and crack pattern

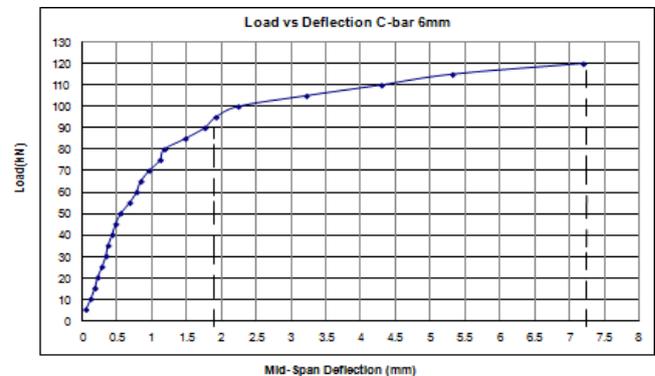
Failure modes of beams with spiral rib and diamond rib conventional HYSD rebars, mild steel rebars and PSWC rebars are tabulated in the Table 9.



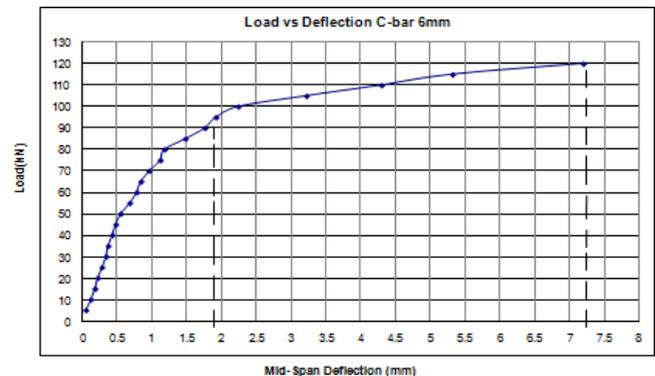
(a) Load vs. deflection behaviour for Spiral Rib HYSD rebar beams



(b) Load vs. deflection behaviour for diamond rib HYSD rebar beams



(c) Load vs. deflection behaviour for PSWC rebar (4mm deformation) beams



(d) Load vs. deflection behaviour for PSWC rebar (6mm deformation) beams

Fig. 30. Load-deflection behaviour of tested beam for ductility calculations.

Table 9. Ductility and energy absorption capacity of tested beams.

S. No.	Type of specimen	Displacement Ductility	Energy Absorption Capacity (kN-mm)
1	Beams with spiral rib HYSD rebars	3.80	12.45
2	Beams with diamond rib HYSD rebars	2.26	20
3	Beams with mild steel rebars	-	-
4	Beams with PSWC rebars (4mm deformation)	5.54	33
5	Beams with PSWC rebars (6mm deformation)	3.75	31.3

Figs. 31-35 show the failure mode and crack pattern for different categories of beams. It is observed that HYSD rebar beams had undergone diagonal shear failure while the mild steel and PSWC rebars reinforced beams had undergone flexural failure. In case of HYSD rebar beams, cracks originated near the support and propagated in the same region with further application of load, while in case of mild steel and PSWC rebar reinforced beams cracks originated at the centre of the beam registering tension failure and new cracks propagated near to the support on further application of load. It can be visualized from the figures that the failure mode of both, the conventional rebar such as HYSD rebar (diamond rib) and mild steel rebar reinforced concrete beams and that of PSWC rebar reinforced concrete beam was found to be nearly similar.

It is to be noted that crack width of the PSWC rebar reinforced beams were found to be less than that of conventional rebar reinforced beams. An unusual behaviour

was captured in mild steel reinforced beams, the failure was under flexure but at one end of the beam, concrete was pushed out, which could be due to the 'L' bent provided at the end of the rebars. This behaviour was not captured in case of PSWC-rebars reinforced beams although the failure was under flexure. In PSWC rebar beams, the crack has originated at the trough portions of the curve, which tends to get straight while the beam is deflected. These portions exert pressure on the cover concrete while straightening and only crack formation commences in those regions while preventing pushing out of concrete.

7.5. Analytical results

It is observed that analytical results also give good agreement with experimental results. Fig. 36(a-c) shows the deflection of different beams obtained from the analysis.

**Fig. 31.** Failure pattern of beams reinforced with spiral rib HYSD rebars.**Fig. 32.** (continued).



Fig. 32. Failure pattern of beams reinforced with mild steel rebars.



Fig. 33. Failure pattern of beams reinforced with diamond rib HYSD rebars.



Fig. 34. Failure pattern of PSWC rebar (4mm deformation) reinforced beam.

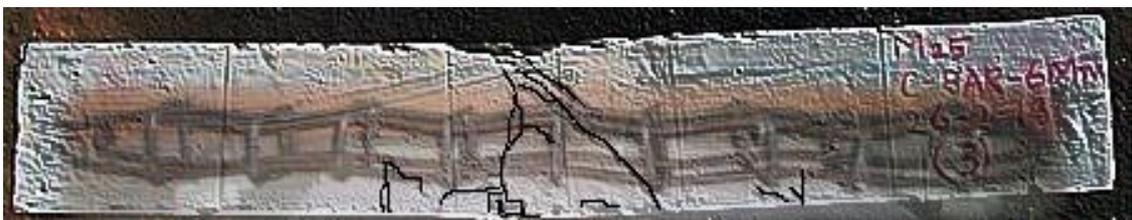
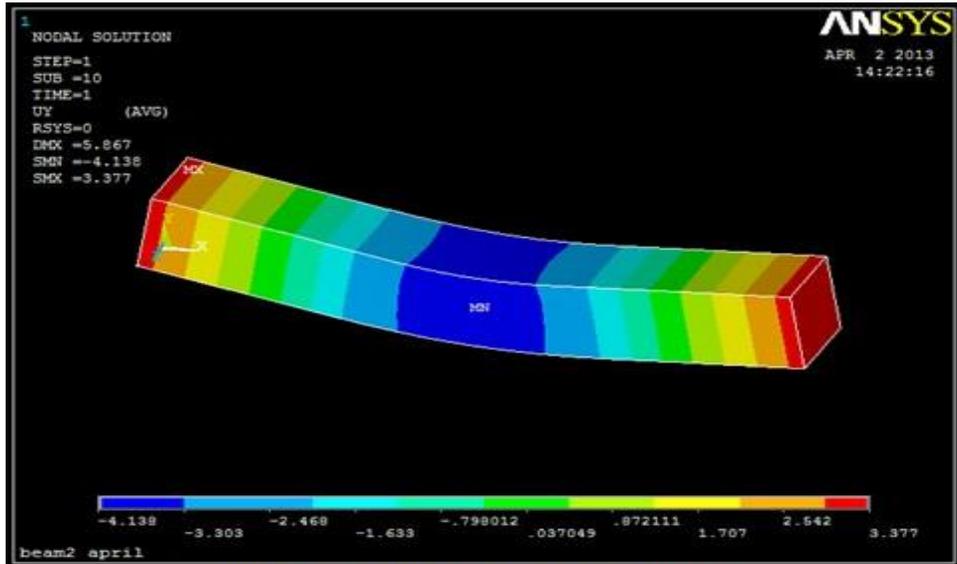
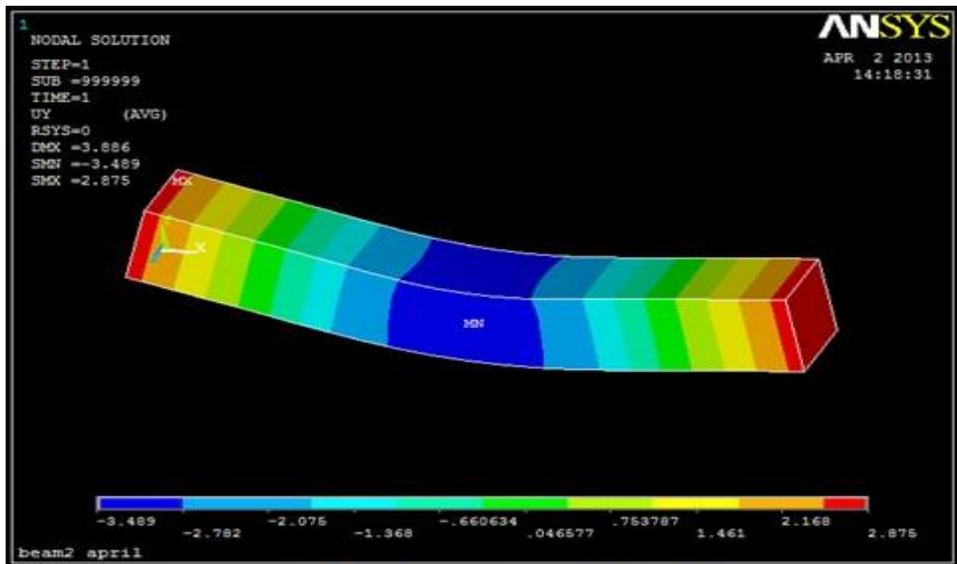


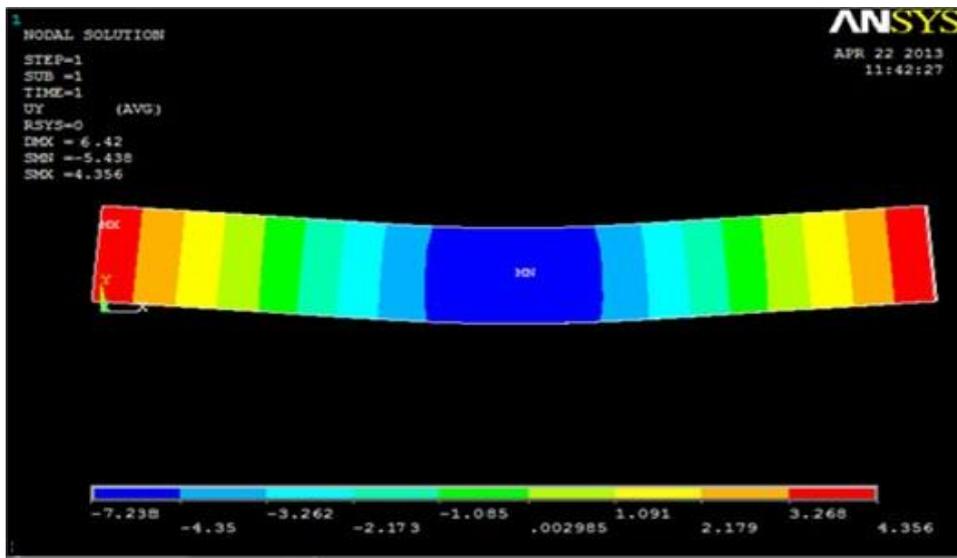
Fig. 35. Failure pattern of PSWC rebar (6mm deformation) reinforced beam.



(a) Deflection of HYSD rebar reinforced beam



(b) Deflection of MILD STEEL rebar reinforced beam



(c) Deflection of C-bar 6mm reinforced beam

Fig. 36. ANSYS deflection pattern for beams: (a) HYSD; (b) Mild steel; (c) PSWC rebars.

8. Conclusions

The test results obtained for PSWC rebar beams are interpreted and compared with HYSD and mild steel rebar beams and following conclusions are drawn:

- Incorporation of PSWC rebars as reinforcement in reinforced concrete beams has enhanced the ductile behaviour of the beams as compared to conventional HYSD and mild steel rebar beams.
- The energy absorbing capacity has increased significantly for beams reinforced with PSWC rebars when compared with conventional HYSD and mild steel rebar beams.
- The load-deflection behavior of PSWC rebar reinforced concrete beams was found to be similar to that of HYSD rebars irrespective of deformation level. The ultimate load carrying capacity of PSWC rebar reinforced beams is found to be less than that of HYSD rebar beams. This could be attributed to low compressive strength of concrete and yielding nature of PSWC rebar during the test.
- The failure mode of PSWC rebar reinforced concrete beams are found to be similar to that of HYSD rebar beams and crack width of PSWC bar reinforced beams are found to be smaller than HYSD rebar beams.
- The deflections of PSWC rebar reinforced beams were found to be higher than HYSD rebar beams which exhibits ductile behaviour of PSWC rebar reinforced beams.
- The PSWC rebar beams offers good flexural performance enhancing the ductility and energy absorbing capacity irrespective of deformation levels.
- The analytical investigation from ANSYS gave good agreement with the experimental results.

It is concluded that PSWC rebar has the potential to replace conventional HYSD rebar. Further study needs to be done to optimize the profile level and stirrup locations; and usage with high concrete grade to get maximum benefit.

REFERENCES

- Gagg CR (2014). Cement and concrete as an engineering material: an historic appraisal and case study analysis. *Engineering Failure Analysis*, 40, 114-140.
- Garden HN, Quantrill RJ, Hollaway LC, Thorne AM, Parke GAR (1998). An experimental study of the anchorage length of carbon fibre composite plates used to strengthen reinforced concrete beams. *Construction and Building Materials*, 12(4), 203-219.
- Goyal A, Pouya HS, Ganjian E, Claisse P (2018). A review of corrosion and protection of steel in concrete. *Arabian Journal for Science and Engineering*, 43(10), 5035-5055.
- Hobbs DW (2001). Concrete deterioration: causes, diagnosis, and minimizing risk. *International Materials Reviews*, 46(3), 117-144.
- IS:269 (1989). Specification for Ordinary Portland Cement. Bureau of Indian Standards, New Delhi, India.
- IS:516-1959 (2004). Indian Standard Methods for Test on Concrete. Bureau of Indian Standards, New Delhi, India.
- IS:2720 (1985). Methods of Tests for Soils, Part IV. Bureau of Indian Standards, New Delhi, India.
- IS:4031 (1989). Methods of Physical Tests for Hydraulic Cement. Part 6: Determination of Compressive Strength of Hydraulic Cement other than Masonry Cement. Bureau of Indian Standards, New Delhi, India.
- IS:2386 (1963). Methods of Test for Aggregates for Concrete-Part 1: Particle Size and Shape. Bureau of Indian Standards, New Delhi, India.
- IS:10262 (2009). Concrete Mix Proportioning—Guidelines. Bureau of Indian Standards, New Delhi, India.
- Kar AK (2012). Durability of concrete bridges and viaducts. *The Masterbuilder*, 14(7), 110-130.
- Kar AK (2019). U.S. Patent Application No. 16/260,951.
- Marcos-Meson V, Michel A, Solgaard A, Fischer G, Edvardsen C, Skovhus TL (2018). Corrosion resistance of steel fibre reinforced concrete-a literature review. *Cement and Concrete Research*, 103, 1-20.
- Meddah MS, Bencheikh M (2009). Properties of concrete reinforced with different kinds of industrial waste fibre materials. *Construction and Building Materials*, 23(10), 3196-3205.
- Nanni A (2003). North American design guidelines for concrete reinforcement and strengthening using FRP: principles, applications and unresolved issues. *Construction and Building Materials*, 17(6-7), 439-446.
- Neville AM (1987). Why we have concrete durability problems. *Katherine and Bryant Mather International Conference on Concrete Durability*, American Concrete Institute, Detroit, ACI SP-100, 21-48.
- Song HW, Saraswathy V (2007). Corrosion monitoring of reinforced concrete structures – a review. *International Journal of Electrochemical Science*, 2, 1-28.
- Zhao Y, Yu J, Jin W (2011). Damage analysis and cracking model of reinforced concrete structures with rebar corrosion. *Corrosion Science*, 53(10), 3388-3397.