STATIC AND FATIGUE BEHAVIOUR OF SCRAP REBAR SHEAR CONNECTORS IN STEEL- COMPOSITE BEAMS

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Abstract - *In steel-composite structures, shear connectors play a crucial role in the shear transfer between steel and concrete. They are generally used for the transfer of longitudinal shear forces across the steel concrete interface, and also resist the displacement of steel and concrete at the connection, ensuring the composite action. Currently, stud shear connectors being the most widely used shear connectors in composite constructions. Studies have proven that scrap rebars, from the wastage of reinforcement in constructions can also be used as shear connectors. Various shapes of rebar connectors were experimentally tested for their shear behaviours under static loading. However, shear behaviour of the rebar connectors under cyclic loading has not been studied and needs investigation. This paper presents an experimental study of the shear behaviour of rebar connectors of different shapes under monotonic loading cases and analytical study of the same under cyclic loading. Rebar connectors of different shapes such as open link, closed stirrups, circular spirals, rectangular spirals, v-shaped are studied. Each rebar connector was attached to steel flanges by means of welding. Specimens are made for each connector with adequate reinforcements if needed. Push-out tests are conducted on each specimen to determine its ultimate strength, Elastic stiffness, load-slip characteristics, and failure patterns. The experiments are carried out for monotonic loading and analysis of specimen under cyclic loading in ANSYS software is conducted and results were compared.*

Key Words: **Steel- Composite Structures, Stud Shear Connectors, Rebar Shear Connectors, Push-Out Tests, Shear Behaviour**

1. INTRODUCTION

Steel-concrete composite structures are those consisting of structural members which are made of two or more different materials, such as steel and concrete. The main advantage of composite structures is that the properties of individual material can be utilised to form a single unit that performs overall better than its constituent materials. Some composite structures other than steel-concrete include; steel-timber, timber-concrete, plastic-concrete and so on. As it is known, in steel-concrete composite structures, the concrete acts well in compression, but it lacks resistance in tension. Steel can be very strong in tension, even when it is used only in comparatively small amounts. Steel- concrete composite elements use the concrete's compressive strength along with the tensional resistance of steel and when they are connected together, this results in a lightweight and highly efficient unit. For this necessary and an efficient connection must be ensured between the steel concrete interface and that can be achieved by shear connectors. In steel-concrete composite structures, shear connectors play a critical role in the shear transfer between the steel and concrete members. The seismic capacity and ductility of the steel-concrete composite structural system entirely depends on the shear transfer between steel-concrete interfaces. The headed studs are the most commonly used shear connectors. They are popular mainly due to its proven performance and ease in installation. Studies have been conducted in determining the shear capacities of headed studs under monotonic loading through standard push out tests [Ollgard. J. O, et al. 1971]. Several different types of shear connectors have been studied as alternatives to the shear stud connectors and these are reported in the literature. The rebars can also be used as a shear connector in accordance with various international codes. Rebar shear connectors have the advantage among other types of shear connectors considering the fact that it can be fabricated to required shape along with reinforcement for slab. The wastage of reinforcement in the Indian construction industry is higher than in other countries due to manual methods of bar bending and cutting. Hence, rebar shear connectors can be made using rods available from the wastage of reinforcement. Conventional push out tests with single level shear connector resulted in the separation of slab portion from the composite structure. Therefore, modified push out test was suggested which facilitates performance of push out tests with standard machines.

Many experimental studies conducted in recent years concluded that a comparative study between the behavior of channel and angle shear connectors was conducted [Shariati, et al. 2013]. Compiled experimental and analytical studies of some shear connector made of rolled steel sections (Tee, Channel, Plate shapes) besides non-welded shear connectors [Ali Shariati, et al, 2012]. Advantages and disadvantages of those connectors were presented.

Studies on the behavior of channel shaped connectors and recommended empirical formula for the strength of connectors [Amit Pashan, et al, 2006]. Also, studies were conducted to determine the behavior of channel connectors both experimentally and analytically [Shervin Maleki, et al.,2008]. Usability of standoff screw as shear connector was studied [Alander, C. C, et al., 1998], showing standoff screw to be an effective alternative to stud shear connector. The behavior of perforated steel plate as shear connector has been also studied [Kim. B, et al., 2011]. Use of straight rebar pieces as shear connector, which resulted in higher ultimate strength has been also studied [Koken. A, et al., 2014]. The headed stud connectors when provided with rubber sleeves, they showed excellent deformation recovery and FEM results were also presented in accordance with it [B. Zhuang, et al., 2018]. Studies were also conducted in order to study the shear behaviour of studs under both monotonic and cyclic loading [C. Zhai, et al., 2018]. Usage of rebars as shear connectors instead of studs and experimental determination of ductility was also studied [B. Saravanakumar, et al., 2018]. Studies also showed the tie-bars subjected to cyclic loading exhibited lesser values for the shear capacities and shear slips than those subjected under monotonic loading [C. Zhai, et al., 2018]. Kisaku [13] based on the experimental results, attempted to empirically a model perfobond-rib connector which was necessary to predict the shear slip behaviour of connectors under cyclic loading. A new type of a mixed shear connector was introduced by combining both headed stud and perfobond rib connectors at the same flange of the steel beam [14]. The shear capacity of the mixed shear connector increases with the increase of the stud diameter, rebar diameter, hole diameter, stud strength, rebar strength, and concrete strength. Hildebrand [15] their research focused on prediction of stud welding process behaviour, stud diameter effects, and influence of the material strength and hardening behaviour as well as metallurgical effects on fatigue strength. Experimental assessment of angle shear connectors under monotonic and fully reversed cyclic loading in HSC did not achieve required ductility and specimens showed a lower strength degradation when they were subjected to low cyclic fatigue loading [16]. Use of straight rebar pieces as shear connectors has been studied by Koken, et al. [17], reporting that such connectors resulted in higher ultimate strength in comparison to stud shear connectors. The strength of double shear studs in a favourable position is generally more than that of staggered pairs of shear connectors [18]. Studies also concluded that numerical analysis with finite element based softwares like ANSYS, ABACUS etc, could be used as a supplement to push-out tests [19].

Fig -1 Rebar shear connectors; (V shape, Closed stirrups, Circular spiral, Rectangular spiral, and Open link respectively)

From the above studies the following observations are derived.

(i) Majority of studies are conducted on static and fatigue behavior of most common type of shear connector, i.e., headed stud shear connectors which are welded to the steel beam flange in the steel-concrete interface.

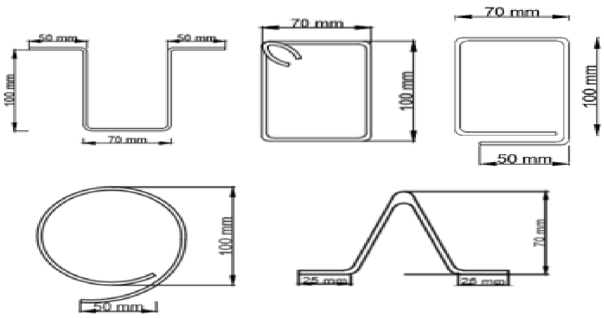


Fig -2(a) Details of rebar connectors

(ii) Most of the works are also concentrated on replacing the type of shear connectors of various shapes such as angle shear connectors, channel shear connectors, perfobond-rib type and mixed shear connectors which are made of rolled steel sections.

(iii) A wide research gap exists in the economic usage of scrap rebars obtained from cutting and bending of bars in Indian construction industry. Hence it is felt that the potential of these scrap rebars as an economic but effective shear connector needs to be explored further.

iv) Works are carried out to determine the shear behavior of the scrap rebars as shar connectors under monotonic loading. Hence, it is required to ensure the effectiveness of these connectors under fatigue loading.

v) Analytical studies were also carried out as a supplement to the push out tests conducted for both monotonic and cyclic loading.

Based on these observations, this investigation is aimed at studying the effectiveness of scrap rebar shear connectors under both monotonic and cyclic loading with a numerical study. An experimental study was conducted for steel-concrete composite beam with different shapes of scrap rebar shear connectors namely, circular spiral, open link, closed stirrup, rectangular spiral and V- shaped connectors as shown in fig.1.

2. EXPERIMENTAL PROGRAMME

For determining the strength of scrap rebar shear connectors, an experimental program was executed. Various codes [20,21,22] give guidelines for conducting standard pushout tests. Total of five specimen were made with different shapes of rebar shear connectors. The rebars are welded on the flange of steel beam. The composite specimen was made up of steel beam and concrete blocks cast upon both flanges of the steel beam in which the shear connectors are welded. Fig.2(b) shows the dimension of specimen cross-section. Fig.2(a) shows the dimension of connectors.

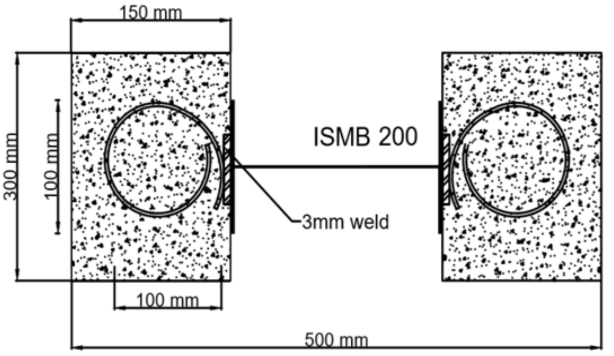


Fig -2(b) Details of circular spiral shear connectors

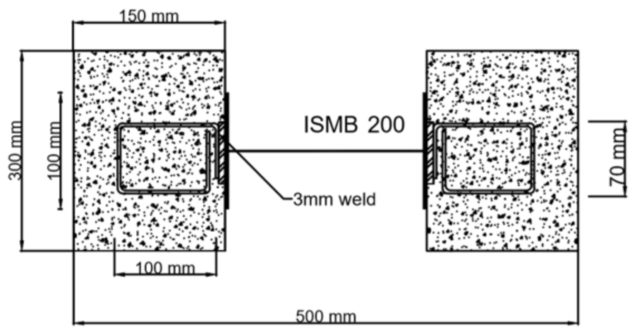


Fig -2(b) Details of rectangular spiral shear connectors

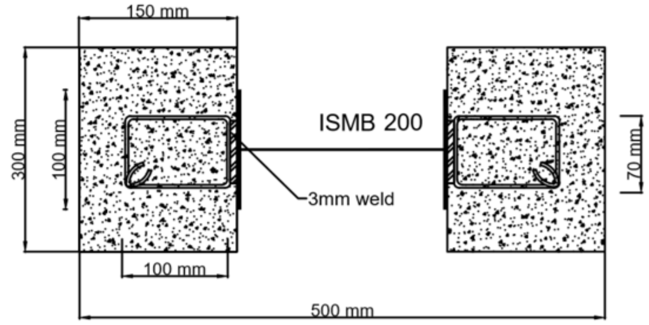


Fig -2(b) Details of closed stirrup shear connectors

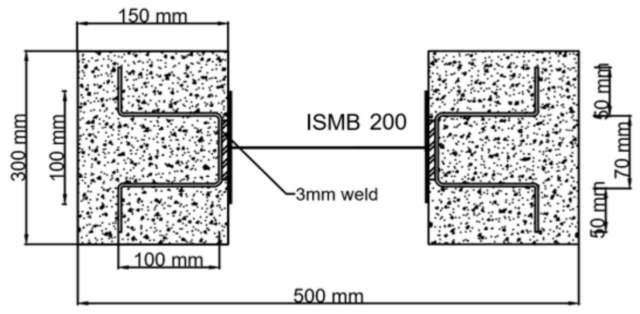


Fig -2(b) Details of open link shear connectors

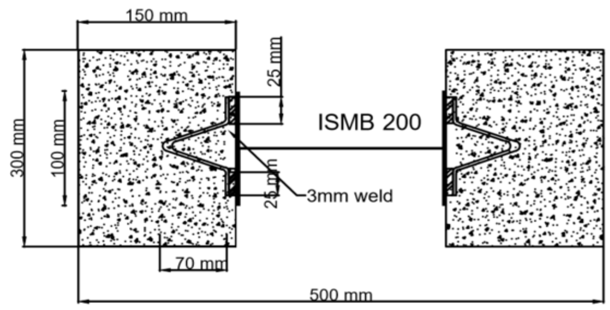


Fig -2(b) Details of v-shaped shear connectors

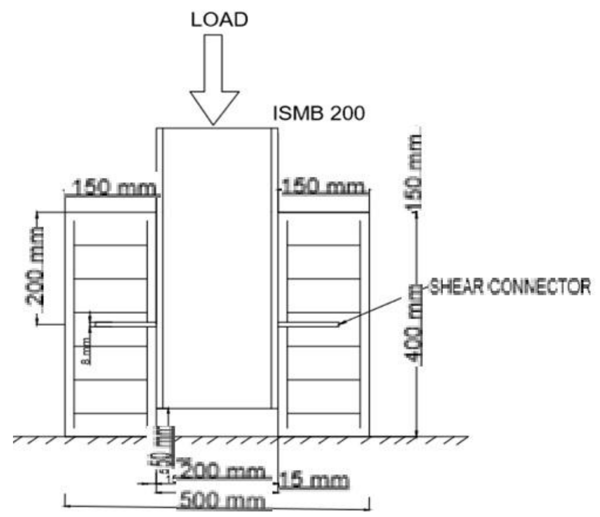


Fig -3 Details of specimen

2.1. Materials

Fresh Portland Pozzolana Cement (PPC) was used for casting of concrete slab. Manufactured sand passing through 4.75 mm sieve and conforming to zone II of IS 383 was used as fine aggregate. 12.5 mm down crushed stones were used as coarse aggregates. In order to cast the reinforced concrete slab made of plywood was made for each specimen. The pushout test samples were made using M20 concrete. The concrete mix proportion is shown in table 1. The steel beam used for the experimental study was standard ISMB 200 confining to IS 11384-1985 [21], with a length of 500 mm. The steel beam was cut using gas welding and cut surface as properly grinded. The specimen was fabricated in workshop. The thickness of the steel beam flange was 10.8mm and the yield strength of steel beam was 250MPa. Rebar shear connectors in the form of open links, closed stirrups, rectangular spiral, circular spiral and V-shape as in fig.1 were made from steel bars of 8 mm diameter. Reinforcement cage was provided using 8 mm bars and stirrups using 8 mm bars. The different types of rebar shear connectors were made of 8mm rebars bent into required shapes. For Open link shear connector, the two arms of 50mm length was welded onto the flange surface. Whereas, for V-shaped connector the arm length was 25mm on each side. The extended length of 50mm was welded to the flange in the case of circular and rectangular spiral rebar connectors. The closed stirrup has edge length of 70mm which was welded to beam.

Table -1: Concrete mix proportion

Material	Quantity (kg/m3)
Cement Content	113.30
Fine Aggregate Content	189.035
Coarse Aggregate Content	94.512
Water Content	50.98
Water cement ratio	0.45

2.2. Preparation of specimens

Initially, the concrete floor of laboratory was properly cleaned to avoid undulations. Before casting, the surface of mould was roughly cleaned by sand paper to remove dust and oil to get bonding. The rebars were bent and cut into required shape. The size of weld was taken as 4mm. The position of rebar connectors is shown in fig.3. Concrete slabs of size 300 mm X 400 mm X 150mm, were cast with a clear cover of 25 mm with concrete mix of cube compressive strength 20 N/mm^2, with water-cement ratio 0.45. Four 8 mm diameter bars were used as longitudinal reinforcement and 8 mm diameter stirrups at 75mm spacing was provided as lateral reinforcement. There was a gap of 50mm at the bottom to facilitate slip. After casting, the specimens were demolded after 24hrs and immediately submerged in clean fresh water of the curing tank. After the completion of curing period of 28 days, the specimens are taken out and tested. Specimen to be tested is shown in fig.4.

2.3. Experimental procedure

The push-out specimens under monotonic loading were loaded using Universal Testing Machine of 1000 kN capacity. The load was applied on the upper end of ISMB 200. The monotonic push-out specimens were placed on the platform of UTM as shown in fig.4. The specimen was loaded at a constant rate until failure of specimen occurs. For monotonic loading, the loading condition was controlled by the load. The load was continuously increased till the failure of specimen. Each time cracking of concrete, failure load and slip at regular intervals of load increment were noted carefully. The load and displacement of the samples were recorded by UTM till failure of specimen.

2.4. Experimental result

2.4.1 Failure mode

The specimen exhibits a failure mechanism characterized by shearing at the slab-beam interface. The common different failure modes observed in the previous studies were, namely fracture of connector, weld failure of connector and concrete crushing-splitting. In all the specimens, the failure was observed as weld failure for the loads applied. None of the specimens showed concrete crushing-splitting failure. This is due to the hoop type transverse reinforcement which confined the concrete near the vicinity of the connector. The details of failure type are shown in fig.5.

2.4.2 Shear capacity and Load- slip characteristics

All rebar shear connectors showed higher shear capacity, compared to stud shear connectors. The ultimate load for rebar shear connectors would be more if higher size of weld were to be used. The magnitude of increase in ultimate strength is much higher (21% to 70%) in Saravanakumar, et al, compared to 7% in the study of Koken and Koroglu, et al. [8] Fig.5 shows the ultimate shear strength of shear connectors. The circular rebar shear connector obtained maximum load of 56.57 kN. The slip at maximum load for circular spiral was 7.4mm which was 92.5% of diameter of connectors. Also, circular rebar shear connectors showed decrease of 25.76% from that of studies conducted by Saravanakumar, et.al.[11].

Fig -4 Specimen cast for Monotonic loading

The open link type connector showed a decrease of 15.43% from the study, with an ultimate load of 50.26 kN and slip at maximum load is obtained as 7 mm which is 87.5% of diameter of connector. The closed stirrups obtained an ultimate load of 53.5 kN per connector and slip of 4.6mm which is 57.5 % of diameter of connectors. Also, they showed a decrease in strength by 19.24%. The rectangular spiral observed a slip of 4.30mm which is 53.75% of diameter of the connectors at a maximum load of 46.19 kN. It showed a variation in strength by 14.46%. the V-shaped connectors obtained an ultimate load of 53.6 kN with a slip of 6.4mm. From the experimental results, it is observed that the circular spiral rebar shear connectors exhibit higher ultimate strength when compared to the other shapes of rebar shear connectors. The V-shaped rebar shear connector which is studied in this experiment is having a similar strength of that of closed stirrups with a capacity of 53kN. However, all the rebar connectors showed a decrease in the ultimate load capacity from the literature. Fig.7 shows the load-slip characteristics of different rebar shear connectors. This may be due to the replacement of OPC cement grade with that of PPC. Also, the quality of materials and the efficiency in the compaction of concrete during the casting determines the ultimate strength of the specimen. The average ultimate strength and slip obtained of connectors is listed in table 2.

2.4.3 Shear stiffness

The shear stiffness has been calculated in the linear range of load-slip curve and tabulated in the table 2. The shear stiffness is ultimate shear capacity of connector upon maximum slip obtained. Load-slip plots indicated that all the rebar connectors provide superior ductile behaviour. The linear load range of circular is about 50%, open link is 44%, closed stirrup is 30%, rectangular spiral is 35% and V-shape is 31%.

Fig- 5 Test setup for Monotonic loading

Table- 2: Shear stiffness comparison of rebar shear connectors

Specimen	Average Ultimate strength per connector (kN)	Average Elastic stiffness (kN/mm)
Circular spiral	56.57	15.29
Open link	50.26	14.36
Closed stirrups	53.5	10.38
Rectangular spiral	46.19	8.63
V shaped	53.6	16.75

Fig -6 Failure type in specimen: connector part attached to

(a) steel beam (b) concrete

3. ANALYTICAL STUDY

Inorder to understand the strength and ductility limits of the specimen, numerical models of the specimen were prepared and analysed. The specimen prepared for the experimental programme is modelled in the software and boundary conditions are applied for analysing both static and fatigue behaviour of connectors. Materials are modelled in Solidworks and are exported to Worbench setup for applying boundary conditions. The nonlinearity among material, geometry and contact were taken into consideration. A finite element model was prepared using the general-purpose finite element software. The model consist of mainly steel beam, concrete, connectors and reinforcing bars which are modelled in the software ANSYS WORKBENCH 16.0. Though the model was symmetric the entire portion was established for analysis. The materials were selected from the material library. Material property of the model is defined when the model is transferred to the setup part in ANSYS WORKBENCH 16.0.

3.1 Material modelling

The concrete part of the specimen was modelled as concrete nonlinear. Fig.2(b) shows the dimension of model. The modulus of elasticity of M20 concrete was 22367 MPa and the yield strength was 250MPa. The uniaxial stress-strain curve is defined in the properties of concrete. Mainly two stages of compression can be seen in concrete. The first being the ideal elastic stage in which the compressive stress gradually increased a proportional limit. The second part is the nonlinear part, which is parabolic and shows the nonlinear variation of compressive stress for the strain. The steel beam was also modelled as non linear. The yield strength of steel beam is 250MPa and elastic modulus is 200000 MPa. Five different shapes of rebar shear connectors were prepared for the analysis. Fig.2(a) shows the dimension of connectors. The connection between steel beam and connectors were welded connetion. Hence, rigid connection was assumed. The bond between concrete and Steel beam (ISMB 200) is assumed to be frictionless. Mesh controls allows establishing factors such as the element shape, mid side node placement, and element size to be used in the solid model. The generate mesh operations uses all defined meshing controls as input to generate a mesh. The composite structure is fixed at base and steel beam is allowed to move vertically due to the application of load. The uniform load was applied on the top of the steel beam and the two concrete blocks were supported at the base.

In structural analysis, for example, we may apply wind loads in one load step and gravity in a second load step. Load steps also are useful in dividing a transient load history curve into several segments. Sub steps are incremental steps taken within a load step. They are mainly used for accuracy and convergence purposes in transient and nonlinear analyses. Sub steps also are referred to as time steps- steps appropriated a period of the time.

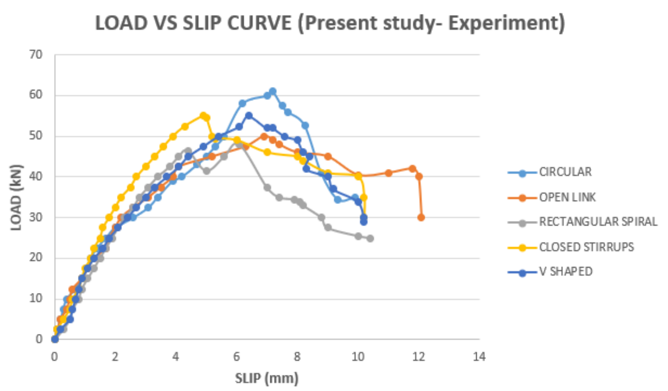


Fig -7 Load – slip characteristics of connectors under monotonic loading (Experimental)

3.2 Validation of model

Nowadays, the development in the software modelling and analysis of structural elements has become simple. The finite element analysis is one such tool. Selection of proper element types is another important criterion in finite element analysis. For monotonic or static loading valdation, Khushaboo et al, 2017 was considered. In the literature, RC beam of 6000mm x300mm x500 mm size, is designed for M20 concrete and Fe 415 steel. The simple span of the beam is reinforced with sufficient steel at bottom and top with 12mm bars which is the hold in place with the help of 2 legged 8mm stirrups at 250mm c/c. The specimen was modelled and transferred to the setup part of workbench for analysis. Khushaboo and Imran Alam, (2017) in their experimental study conducted on the flexural behaviour of the concrete beam with glass fibre reinforced polymer rebar as internal reinforcement [23], obtained the load- deflection graph from which we obtained deviations from the original values within 20% range. Hence, we can infer that the variation in non-linearity of the load- deflection curve may be due to the inability in assumption of the failure criteria.

For the validation of cyclic loading in specimen, the study conducted by B.Zhuang,et al.(2018) on the deformation recovery of rubber sleeved stud connectors is referred [9]. The steel- concrete composite ith rubber sleeved studd connectors were modelled and transerred to the setup part of ANSYS Workbench for analysis. The cyclic loading was applied in the tabular form with respect to time. In the literature the analysis was done using ABAQUS. The specimen was applied cyclic loading for positive cycles.

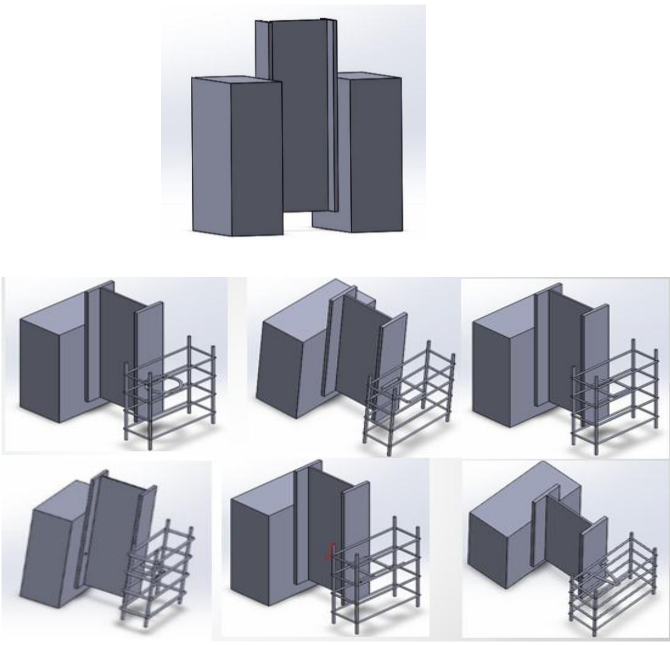


Fig -8 Specimen modelled in Solid works (Circular spiral, Open link, Closed stirrup, Rectangular spiral, V-shaped respectively)

The maximum deformation was obtained as 4.69mm, where as in the literature it was obtained as 6mm. Variation in the results of FE model analysis and that from the literature was negligible. The von mises stress variation of the stud under the cyclic loading program is also determined. The peak value occurred at the stud root. The von mises stress variation as in the literature for the cyclic load upper limit of 112.5 kN is 425MPa. Thus, percentage variation in the von mises stress being 14.4%.

3.4 Static loading

3.4.1 Shear capacity and Load- slip curve

The shear capacity of stud connectors were referred from the literature and all that of rebar connectors were experimentally determined. The table 3 shows the ultimate strength and maximum slip obtained for different connectors. Therefore, monotonic loading was applied to all the specimen in number of steps. The validation results are obtained by combining the results from the literature, experimental program conducted during validation and the analytical validation of the steel- concrete composite specimen with different types of rebar shear connectors. Fig.11 shows the load-slip characteristics of connectors under static loading. From the graphs, it can be inferred that the analytical results are analogous to the experimental results obtained.

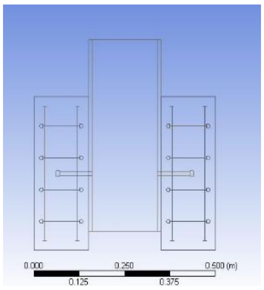


Fig -9 Model of stud shear connector specimen

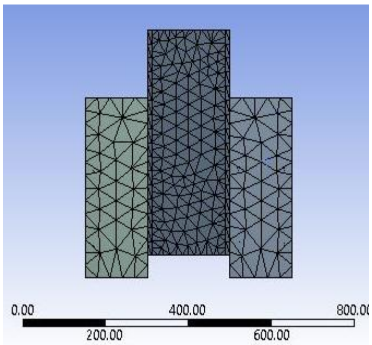


Fig -10 Meshed model of shear connector specimen

3.4.2 Von mises Stress

When a body is in equilibrium state and is subjected to a surface force, it tends to deform until it reaches a new state of equilibrium. It is also referred to as deformed state. Here, the external forces which characterize what is called the stress and the deformation of the body, which characterizes strain. An equivalent tensile stress or equivalent von Mises stress, is used to predict yielding of materials under multiaxial loading conditions using results from simple uniaxial tensile tests. It is used to determine if a given material will yield or fracture. It is mostly used for ductile materials, such as metals. The fig.12 shows the variation of Mises stress for different connectors. The maximum von mises stress occurred at the interface between steel and connector at the root of the connector. As most of the specimen failure was due to weld failure. From the static analysis, the von mises stresses of stud, circular spiral, open link, closed stirrup, rectangular spiral and v-shaped connectors were 310Mpa, 493.96Mpa, 292.08Mpa, 260.41Mpa, 311.84Mpa and 301.04Mpa respectively.

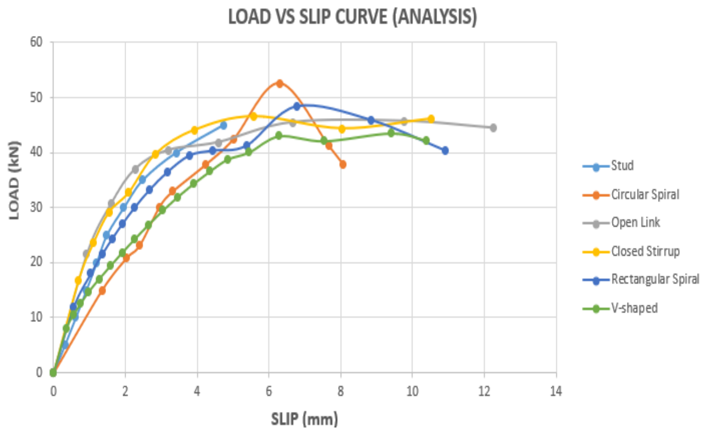


Fig -11 Load-slip curve of shear connectors under monotonic loading (Analysis)

Table 3: Ultimate strength and maximum slip obtained for static loading

Specimen	Average Ultimate Strength per Connector (kN)	Slip at max. load (mm)
Stud type	45.15	4.91
Circular spiral	49.85	8.08
Open link	47.47	7.14
Closed stirrups	46.12	4.65
Rectangular spiral	45.42	4.37
V shaped	44.24	6.49

3.5 Cyclic or fatigue loading

3.5.1 Shear capacity and Load- slip characteristics

Fatigue analysis is mainly carried out to identify the capability of the material to survive the many cycles of loading. While many parts may work well initially, they often fail in service due to fatigue caused by repeated cyclic loading. The repeated loading may effect in the intialisation of micro-cracking. . For the cyclic loading the maximum slips for different specimen were 0.28mm for stud type connector, 1.9mm for circular spiral, closed stirrup having 0.27mm, open link with 0.22mm, rectangular spiral and V-shape connectors with 2mm and 0.3mm respectively. At each load stage, there was increment in the slip obtained in the loading program. The maximum slip of 2mm was obtained rectangular spiral type of connector. The load-deflection hysteresis loops plays an important role and it must be generated to evaluate the structural performance during seismic events. The Load-deflection hysteresis response indicates the energy dissipation capacity of a structure by combining the area enclosed by the individual hysteresis loops. Load-deflection hysteresis loops of all connectors are shown in Fig.13. The load-slip hysteresis was within the elastic range for the upper limit of loading cycle reaches 50% of its ultimate capacity. The maximum slip was obtained as the upper limit of loading cycle reaches to 90% of its ultimate shearing capacity. Maximum slip developed indicates higher energy dissipation under loading cycle.

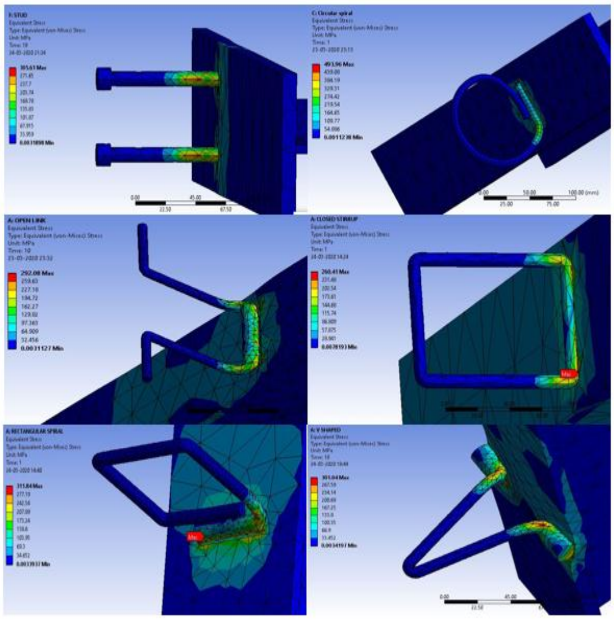
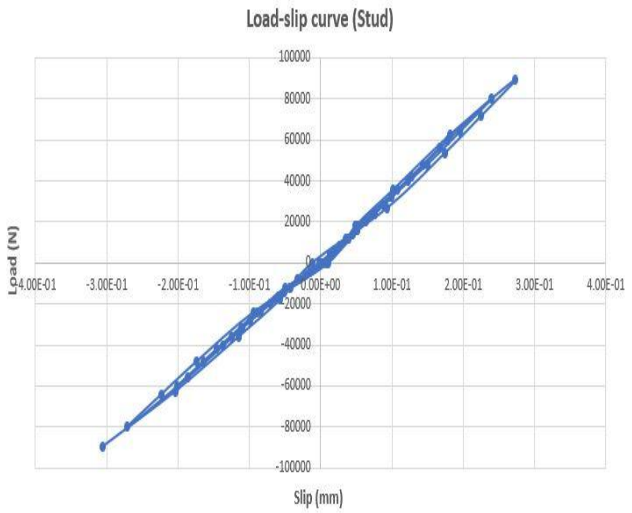


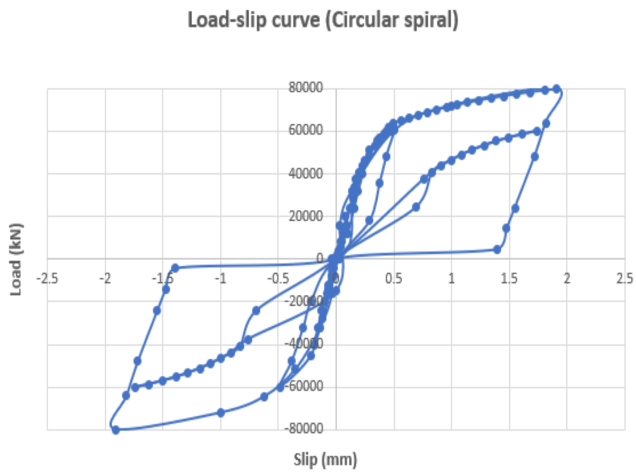
Fig -12 Von Mises stress in shear connectors under monotonic loading

3.5.2 Von mises stress

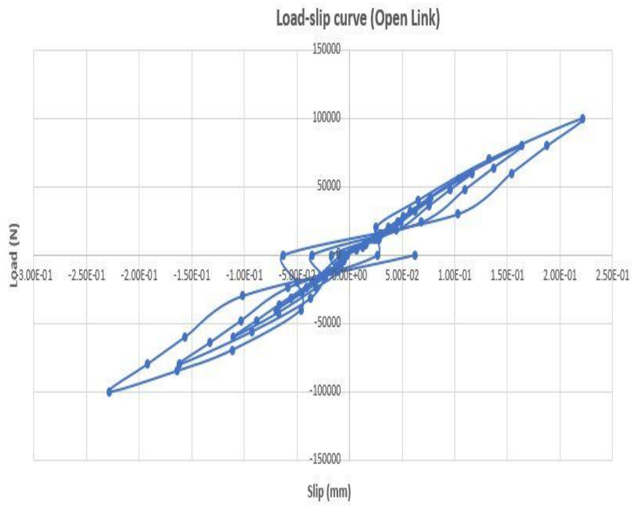
For a structure under loading, the stresses are always not uniaxial. Hence, the stresses in all directions are combined and represented as von mises stress. The von mises stress is the maximum stress achieved when the connector reaches its yielding point. Therefore, it plays a significant role in the understanding of failure behavior of structures. The von mises stress in the connectors for cyclic loading program are shown in the fig.14. The headed stud obtained a maximum stress value of 305MPa in the loading cycle. The open link shear connector obtained stress of 317MPa. Closed stirrup, Circular spiral, Rectangular spiral and V shaped shear connectors obtained stresses of 321, 521, 342 and 332MPa.



(a) Stud type



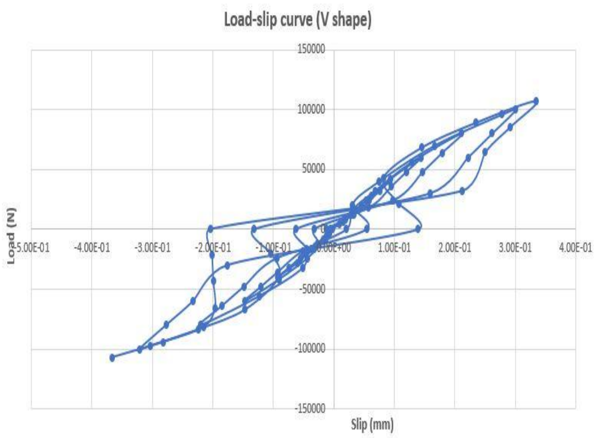
(b) Circular spiral type



(c) Open link type

(d) Closed stirrup type

(e) Rectangular spiral type



(f) V-shaped type

Fig -13 Load-slip curves of shear connectors under cyclic loading

The von mises stress distribution of different shear connectors was obtained from the analysis. Under both static and fatigue loading procedure, the highest stress was shown by circular spiral type shear connector with a value of 493.96 and 568.12MPa for static and fatigue loadings respectively. The comparison of equivalent von mises stress distribution for various connectors are noted in the table 4 given.

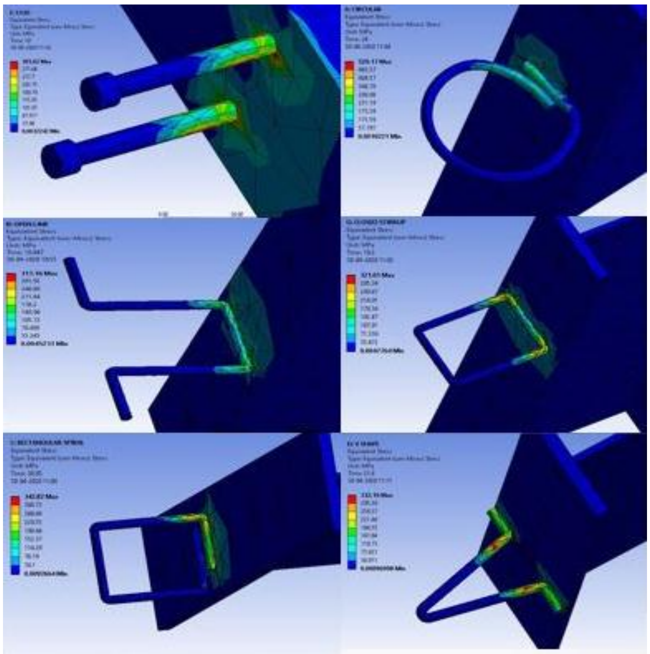


Fig -14 Equivalent Von mises stress distribution of shear connectors under cyclic loading

Table 4: Comparison of Equivalent Von mises stress in connectors

Type of Connector	Static Von mises stress (MPa)	Fatigue Von mises stress (MPa)
Stud type	310.00	305.02
Circular spiral	493.36	568.12
Open link	292.08	317.00
Closed stirrup	260.41	321.14
Rectangular spiral	311.84	342.10
V Shaped	301.04	332.19

3.5.3 Energy Dissipation

In the case of structures, survival after a seismic loading mainly depends on its energy dissipation capacity. Greater the energy dissipation, better the performance of specimen. For a RC member subjected to cyclic loading, it is a relevant parameter. In a typical loading cycle, the energy injected into the structure has two forms: dissipated energy and recoverable energy. Total energy absorbed by the system is the total of dissipated and recoverable energy. The energy dissipated encloses the area of the hysteresis loop and denotes the capacity of a structural element to mitigate the effects due to seismic events, inelastically through inelastic behaviour of reinforcing steel which in turn results in excessive cracking and permanent deformation. The energy dissipated during each loading cycle is the area within the load-deflection hysteresis loop which is calculated using the trapezoidal rule. The energy dissipation for different types of connectors under cyclic loading program is listed. It can be observed that for all the beams, the energy dissipated in the first cycle of each displacement level was greater than that in the subsequent cycles. The headed stud shear connector has an energy dissipation of 43700J. The highest energy dissipation was recorded by Rectangular spiral shaped connector with 169000J, followed by circular spiral having 197000J. The closed stirrup shaped connector produced 34400J, Open Link with 25300J and V-shaped connector having 65500J. The energy dissipation of various connectors is plotted in the chart fig.15. The possible explanation of greater value of dissipated energy in first cycle of loading is that when the loading increases, deflection is increased which causes the cracks to extend. But the connectors present in the path of the cracking tries to resist their propagation causing much energy dissipation than the subsequent cycles.

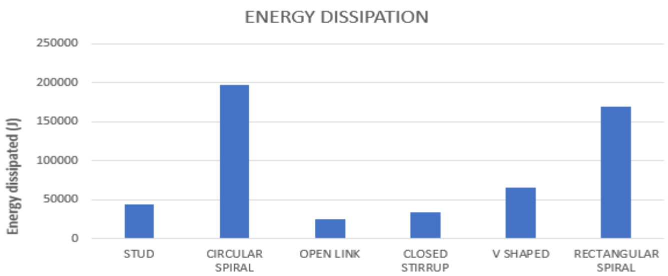


Fig -15 Energy dissipation of shear connectors under cyclic loading

4. CONCLUSIONS

In this study, five push-out specimens were tested experimentally and analytically to study the shear behavior of rebar shear connectors under the static and fatigue loading. The parameters considered for the study includes different type of connectors and shapes of rebar connectors as well as the load procedure. The failure mode, shear capacity, slip, load-slip characteristics, shear stiffness and energy dissipation capacities of the various rebar connectors were studied. The steel-concrete composite beam specimen with different shear connectors were also modelled and analyzed to obtain FEM results and compared with experimental results. The findings from this study can be summarized as follows:

- The failure modes observed for the experiment conducted, where all the specimen was subjected to static loading is weld failure. It is viewed that the load-slip characteristics and failure mode showed the low strength of the heat affected zones in the welded joint was a prime reason for the reduction in strength or shear capacities of shear connectors under monotonic loading.

- The analysis for studying the shear behavior of rebar connectors under static loading revealed comparable results with that of the experiment conducted. In static loading, the circular rebar connector showed the maximum ultimate shear capacity of 56.57kN with a maximum slip of 7.4mm. Whereas for analytical study showed 49kN.

- The percentage variation of ultimate shear capacity for static loading experimental and analysis were 13.38% for circular spiral, 5.5% for open link, 13.79% for closed stirrups, 1.67% for rectangular spiral and 17.46% for V-shaped rebar shear connectors.

- The shear capacities and slips of the rebar and stud connectors for fatigue loading analysis were much below compared to that of static loading. The maximum slips obtained by rectangular spiral and circular spiral were 2mm and 1.9mm respectively. The circular spiral seemed to be not much efficient when it was under cyclic loading condition as repeated loading cycles enhances more separation behavior due to weakening of corners.

- The Von mises stress under both loading cases revealed the circular spiral is having highest Von mises stress with 493MPa in static loading and 568.12MPa in fatigue loading followed by Rectangular spiral, Headed stud, V-shaped, Open link and Closed stirrups.

- The highest energy dissipation for cyclic loading analysis was recorded by circular spiral having 197000J followed by rectangular spiral shaped connector with 169000J, whereas the headed stud shear connector has an energy dissipation of 43700J. Maximum slip developed indicates higher energy dissipation under loading cycle.

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