COMPARATIVE STUDY ON EFFECTIVE USAGE OF FRP AND STEEL EXTERNAL BONDING FOR STRENGTH ENHANCEMENT OF RC BEAMS: A REVIEW

Bareera A[1], Chandana M[2]

[1]M Tech Structural Engineering, Department of Civil Engineering, Kerala Technological University, Vedavyasa Institute of Technology, Kerala, India

[2]Assistant Professor, Department of Civil Engineering, Vedavyasa Institute of Technology, Kerala, India

ABSTRACT

Retrofitting became an important aspect in structural engineering due to increased loading requirements and changes in usage. Strengthening using external steel members and fiber reinforced polymer are studied mostly for RC beam. However attaching external steel can increase the dead weight of the structure and thus make an uneconomical section. Instead the FRP usage created a significant enhancement in the shear strength and ductility of beam. The main drawback of FRP is intermediate crack and plate area de-bonding. For this a better anchorage technique and light weighted FRP has to be used. In this sense, this paper presents a review of FRP and steel external bonding on structural member and comparative study is done on the literatures. This paper provides a detailed investigation on effective usage of external bonding on the performance of RC beams and provides the comparative solutions for the research gaps analyzed which have been received small attention in previous studies.

Keyword: *FRP, Steel external bonding, Comparative study, Validation*

1. INTRODUCTION

Many structures are prone to different level of loading due to variation in usage of the structures and seismic hazards. Each structural element needs to be maintained and strengthened for each damages, to avoid risks of collapse. Thus, retrofitting becomes a most important practice to be followed. Varieties of strengthening materials have been introduced in past decades and in recent years. Many of them are proved to be effective in shear and flexural performances. Among them are fiber reinforced polymer external bonding which is better in ductility, corrosion resistance and environmental degradation [2, 4, & 29]. Most of the FRPs are highly flexible and they can form all kinds of shapes. FRPs are mainly bonded with RC beams by using epoxy adhesives. There are different anchorage techniques used for bonding these FRPs with concrete. These anchorages are mainly introduced to reduce the de-bonding failure which is seen in externally bonded FRP RC beams. For this Mohr-Coulomb law and discrete crack approaches were studied as numerical study for understanding the interaction between concrete and FRP [29, 3, 4].

Near surface mounting showed a better solution for de-bonding [11]. U shaped strips are used as anchorage in the case of FRP with RC beams and anchor rods are mainly used in the application of external steel bonding with concrete. Anchorage systems can be used to prevent or delay crack opening at the onset of de bonding or failure of the concrete substrate due to tensile normal forces with certain de-bonding failure modes such as “plate-end” interfacial de-bonding or intermediate crack de-bonding. Type I anchorage mainly deals with anchor fixed at the termination of FRP laminates, and sometimes throughout their entire length. Type I anchorage is shown in Fig 1, in which the FRP on a RC beam soffit used for flexural strengthening is anchored at the laminate end in order to prevent intermediate crack de-bonding and "plate-end" interfacial de bonding[9]. Type II anchorage is used when the transfer length is less than the effective bond length, due to the geometric conditions of the structural member, or to reduce the length of FRP used by increasing the interfacial stress transfer [9]. Type III anchorage is used for providing an alternative stress transfer mechanism where no bond length is available beyond the section. This condition applies when the design section is located at a sheet or plate end, or near an abrupt change in fiber direction, like at the location of an interface between two orthogonal structural members [9].

Retrofitting with external steel bonding was prominent form past decades which have a better application in the case of seismic retrofitting. Mainly the external steel bonding was done by using adhesives and bolting. This made the bolting of RC beams throughout its depth. This created the greater impact in the case of coupled beams [5]. Coupled beams comprises two shear wall or any other elements that are used for withstanding lateral loads are combined with each other. These beams when retrofitted can give better solution in the case of seismic risks. When these structural elements were externally bonded with steel section by bolting, the seismic performance was well improved. Beams subjected to fire damages are retrofitted using bolted side plating. This method involve attaching steel plates to the side faces of RC beam by using bolted connection. This method shown good performance in shear and flexure. Although there can be failure in bolted side plated beams like buckling of steel, flexure failure of beam, BSP brittle failure, bearing failure, plate anchorage failure these beams manage to delay the failure up to large extend. Thus shows a tremendous increase in the shear and flexural strength. Not only the fire damaged beams, but also new structural element with large loading requirement are mainly retrofitted by using steel sections. Angle steel and channel steel sections are mostly used for attaching on the structural element in combination with any other confining materials [31, 29].

In the case of beam-column joints [25] retrofitted with external steel elements which was a joint enlargement method. This method involves attachment of external steel and bolts are not drilled through the RC structure but connection of each external bonded steel are by bolts. The 3D effects of joints retrofitted with steel plates and bolts delays the formation of shear hinge and increase ductility because of formation of flexural plastic hinge in beam and increase the load bearing capacity. Joint enlargement method improved joint behavior in terms of load bearing capacity, ductility, and energy dissipation.

However, the main drawback of these technique is, it is not only costly but also there will be enhancement in the dead weight of the beam. Already, the retrofitting method is provided on a damaged structure. Drilling of bolt throughout the whole depth may create more damage on it and also for avoiding the de-bonding in bolted side plating we are consuming extra adhesives. This may lead to cost enhancement to the project. . Thus the material used for retrofitting should fit for the design requirements. Material should be light-weighted, have enough capacity to undergo large deformations and sustainable. Other consequence which is mainly seen in external steel bonding is partial interaction [16]. There can be both longitudinal and transverse interaction which lead to the movement or separation of steel from concrete interface. Many analytical methods have been studied regarding to reduce these effects in RC beam elements [15]. So this lead to the huge requirement for a better anchoring technique and FRP material which can be used to have good bond with concrete interface and can undergo large deformations. This paper concerns about the several techniques used for beam strengthening and their behavior and drawbacks. Presents about new techniques used for meeting the failure criteria in those methods and compares a previous study done using software and suggest about the new alternatives for the paper.

2. RC BEAMS STRENGTHENED WITH FIBER- REINFORCED POLYMER LAMINATES

Fiber reinforced polymers are made of polymer matrix which is reinforced with fibers. Carbon fiber reinforced polymer (CFRP), Glass fiber reinforced polymer (GFRP), Aramid fiber reinforced polymer (AFRP) and Basalt fiber reinforced polymer (BFRP) are most probably used for strengthening purposes. Rather than as laminates, they can replace the conventional steel rebar in RC structural element. They can also be used as hybrid bars [32, 27] of composite properties and as grid reinforcement, in which stirrups are replaced with grid bars.

Most probably, the high strength was gained by CFRP laminates which have the properties of light weight, high fatigue resistance, high strength to weight ratio and good corrosion resistance [6]. Hence they are mostly used to replace corroded structures and can be retrofitted effectively. They can be either used as flexural strengthening by placing in the soffit of RC beam or as shear strengthening on the shear faces by placing diagonally or as wrapping scheme. Aramid laminates [2] in other hand have the properties of high strength, abrasion resistance, chemical resistance, low density and high impact resistance. They can also be used as U wrap schemes, diagonal scheme (fig 3) and as flexural strengthener (fig 1). But in both FRP sheets, the fact is either they can give a promising result as a strengthening material, they can enhance the cost to some extent. BFRP which have high tensile strength properties are used to replace steel reinforcement in RC beams. Their sheets are used for flexural strengthening in beams which are comparatively less in cost. BFRP have promising result by increasing the number of layers [24, 30, 33]. The fibers applied to the beams were stretched and bonded to the beam surfaces so that no air should left under. One more epoxy layer was applied on the bonded wraps and saturated with the resin.

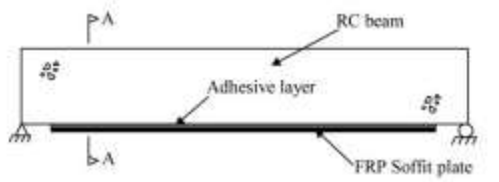

Fig-1: Flexural strengthening with FRP laminates on soffit of beam

Source: S T Smith et al. (2002)

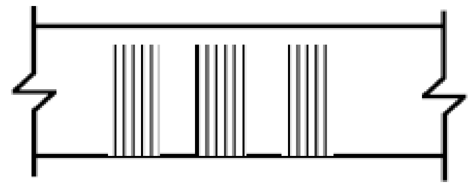

Fig-2: Shear strengthening by placing vertical FRP strips

Source: Amer M Ibrahim et al. (2009)

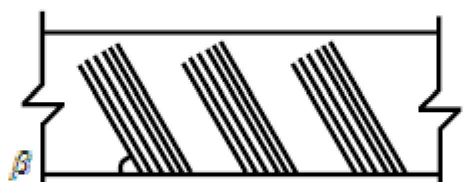

Fig-3: shear strengthening by placing inclined FRP strips

Source: Amer M Ibrahim et al. (2009)

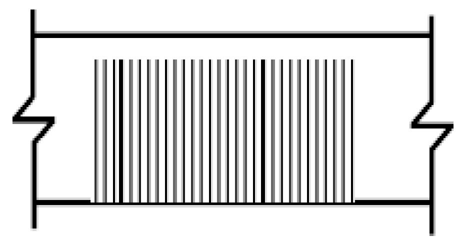

Fig-4: Shear strengthening by placing continuous FRP strips

Source: Amer M Ibrahim et al. (2009)

To increase the flexural capacity of RC beams, the FRP composite oriented laminates are placed along the longitudinal axis of the load bearing component [22]. The composite laminates are bonded to the tension face of the beam. A protective coating is applied over the composite laminate to protect the FRP from environmental exposure effects and to enhance the fire ratings of the FRP strengthening solutions. Three main techniques are utilized to attach FRP composite materials to RC beams for strengthening purposes. Wet lay-up method consists of in-situ forming of the FRP on the surface of the RC beam, using flexible dry fiber fabrics, or sheets and liquid polymers. The wet lay-up systems are commonly used in the field. In this system, the fibers are impregnated and saturated with resin at the site and cured in-situ, at ambient temperatures, resulting in an FRP composite laminate. Plate bonding comprises FRP plates or strips bonded to the most-tensioned side of the strengthened element. An alternative method to the externally bonded techniques mentioned above is the NSM technique. Narrow FRP strips, or small-diameter round FRP bars are inserted into grooves in the soffit of flexural beams. The grooves are then filled with adhesive. The performance of FRP externally bonded to RC beams are such that, it depends on the type of FRP material used, failure modes and type of strengthening adopted. FRP rupture and FRP de-bonding are the two shear failure modes for RC beams shear strengthened with externally bonded FRP reinforcement. Many anchorage techniques and analytical methods have been proposed by calculating the strain developed in FRP with respect to time. Graphical representation on load-deflection curves are used for comparing the performances of FRP strengthened beams and control specimen. In most of the cases the flexural and shear capacities are increasing for strengthened specimen. In shear performance, the main failure mode seen for FRP are peeling failure [24].

3. RC BEAMS EXTERNALLY BONDED WITH STEEL PLATES

Attaching steel section onto side faces of RC beams are studied in recent years. It includes attaching steel plates by using high viscous adhesives. Among them Bolted side plated RC beams gained more interest. This method involves fixing the steel plates on the side faces of RC beams and connecting the steel-concrete interface using bolted connection. This mainly involves the drilling of bolts to its overall depth [18]. In RC beams, the failure modes will be such that flexural failure which is preceded by the yielding of tensile reinforcement and the strain of the outermost tensile reinforcement layer reaches its yield strain. Shear failure is caused in RC beams due to the crushing of concrete and when the maximum compressive strain of the concrete exceeds its crushing strain. Compression zone crushing and compression zone shearing is also another failure mechanism occurring due to the diagonal splitting tension crack in the beam.

Bolted side plated (BSP) RC beams are one of the steel jacketing technique of retrofitting which involves attaching steel plates on the side faces of beams by using pre stressed bolts as connectors. The pre mature de-bonding and sudden failure in different loading condition were observed usually in most of retrofitting techniques. However, the retrofitting methods should be such that it should be compatible for any loading condition. To eliminate de bonding failure, several anchor systems and embedded connector systems have been introduced which led to BSP techniques [14-21]. Failure modes of BSP beams involves flexural failure due to yielding of tensile regions of steel plates, brittle failure due to buckling of compression region of steel plates, bearing failure caused due to the localized crushing of concrete, plate anchorage failure due to breakdown of composite interaction between the plate and concrete and plate buckling due to sudden failure [18].

Fig-5: Bolted side plated beams

Source: Zing Zhang et al (2021)

The strength contributing parameters of BSP beams involves thickness of plate, spacing of bolt anchorage, depth of plate, provisions of stiffeners, and slips in transverse and longitudinal directions. The performance of these types of beams involves two stage behavior. ie, linear growth stage and stiffness decreasing stage. The performance in flexure and shear for BSP beams are more promising. In the case of flexure, capacity increased when buckling restrainers are used [18]. The parameters like number of bolt rows, plate depth, horizontal bolt spacing, plate thickness, shear span ratio, concrete strength, bolt diameter and yield strength of steel plates are mostly affected to the strength. In the case of seismic behavior, thicker steel plate can avoid local buckling and pinching in the load deformation curve, the ductile steel plates possess more deformability and higher energy dissipation via inelastic deformation and the disparity in curvature indicates that translational and rotational partial interactions between steel plate.

4. FAILURES IN RC BEAM STRENGTHENED WITH BOTH STEEL AND FRP

As in external bonded FRPs, external bonded steel too have de-bonding like effects which is termed as "Partial Interaction". Shear force was transferred from the RC beams to the bolted steel plates through the anchor bolts. The displacement of the steel plated lagged behind that of the RC beams, thus relative slips occurs. This is called as partial interaction. This is one the main drawback of bolted side plated RC beams as de-bonding in FRP. Longitudinal interaction involves same variation trend. Magnitudes of slip and slopes of curve increased with increasing load. Moreover they are direction consistent and slips at top edge were larger than slips at the bottom [14]. The parameters like Plate depth should be increased because full plate depth have minimal effect on flexure, bolt spacing should be lessened and provision of stiffener such be as per the relation, slip is proportional to square of stiffness ratio. Likewise, partial transverse interaction is seen in transverse direction mainly they are controlled by the flexural stiffness ratio, β_f and the stiffness of the connection media. These type of partial interaction are negative near the plate ends and positive with greater value near loading points and smaller than longitudinal slips which is studied by [10]. Many models have been proposed in accordance with the design consideration for partial interaction in bolted side plated beams [15]. Recent studies also used epoxy adhesives instead, with bolting for avoiding these failures [29]. The strength gain was obvious for these solution adopted by the researchers. But the fact is that, the dead weight enhancement in the RC structure can lead to an overall uneconomical design. This can make the overall project to be costly. If the structural element is already damaged, then the act of placing extra steel section on them can make over reinforced and the stage of the concrete crushing before the steel section yields. Rather than these, the bolt drilling procedure followed in bolted side plating is mostly throughout the full depth of the beam. This can create more cracks on the concrete interfaces which will be in more complex form. For the sake of brevity, these methods can adopted in seismic retrofitted areas which is mentioned before where load requirements are beyond the control. For the normal retrofitting measures, these methods are more costly. The major requirement in the field of retrofitting is that, the light weighted material external bonding have promising properties for enhancement of strength and the well suited anchoring technique.

Plate end de-bonding failure modes, failure by separation of the concrete cover has been commonly seen [1, 8]. Failure of the concrete cover is initiated by the formation of a crack at or near the plate end, due to interfacial shear and normal stresses becoming high caused by the abrupt ending of the plate. It also forms edge effects in FRP bonded RC beams. The general opinions among researchers is that de-bonding failures of this form are initiated by high interfacial shear and normal stresses near the plate end that exceed the strength of the weakest element, generally the concrete. It is seen that upon de-bonding, a thin layer of concrete generally remains attached to the plate. This shows that the failure occurs in the concrete adjacent to the concrete-to-adhesive interface. It has also been shown that extending the FRP reinforcement as much as possible toward the supports decreases the potential of de-bonding, but does not eliminate it. [1, 8]. For these many researchers suggested possible solutions which is to be adopted during design and placing of FRP laminates. It is studied that the reduction of beam deflection under service loads is mainly influenced by the FRP thickness and its stiffness. The transverse straps placed near to the high moment region within the shear span will be more effective than those near the end of the span [8].

5. COMPARISON BETWEEN FRP AND STEEL EXTERNAL BONDING

As defined above both FRP and steel external bonding are widely studied. Steel sections like angle, channel and plates can perceptibly enhance the flexural strength [29]. They have the large load bearing capacity since the weight, strength and thickness of steel are high comparing to FRPs. Hence, they can bear the large load and deformation even after the concrete crushing. Steel external bonding involves fixing on shear faces of RC beams by using proper adhesives and bolting. This may result in large slip between steel and concrete interfaces which is mainly termed as partial interaction. In case of FRPs, as defined earlier, there are FRP materials which have promising strength enhancement properties. Even though they are prone to de-bonding failures.

As a comparison, the fact is that the steel external bonding can enhance the weight of the specimen which is commonly not acceptable for a structural member. The anchorages like bolting for steel bonding will also be ultimo for it which may create uneven crack patterns in member. In case of FRP, they are contingent on the type and use of anchorages. Better anchorage techniques can provide better strength enhancement without any de-bonding effects in it.

5.1 STUDY OF STRENGTHENING BY STEEL: VALIDATION

The comparative study is made between externally bonded FRP and steel section for retrofitting of RC beams. For the verification of the external bonding method, one of the previous research was verified numerically by finite element modelling software ANSYS 18.1 and ABAQUS CAE 2017. Journal paper Jing Zhang et al (2021) [29] is verified in two different software. Firstly, a simple numerical model is created in ANSYS. From all of the specimen in the literature, a simplest one is chosen to validate. The specimen BCA in which RC T-beam is strengthened with external double steel channel by using epoxy adhesives on the shear faces is chosen. For simplicity, half of model is created in ANSYS because of its symmetry. It reduces the time for solution and meshing. The material properties are fully adopted as per the literature (fig 6). The model created in ANSYS (fig 12) included the strong adhesive layer which was defined as a surface with contact in design modeler. This created the adhesive layer in ANSYS. Boundary conditions given for the model was such that, the bottom support it hinged with a rotation component set free and top support in which an incremental loading was provided.

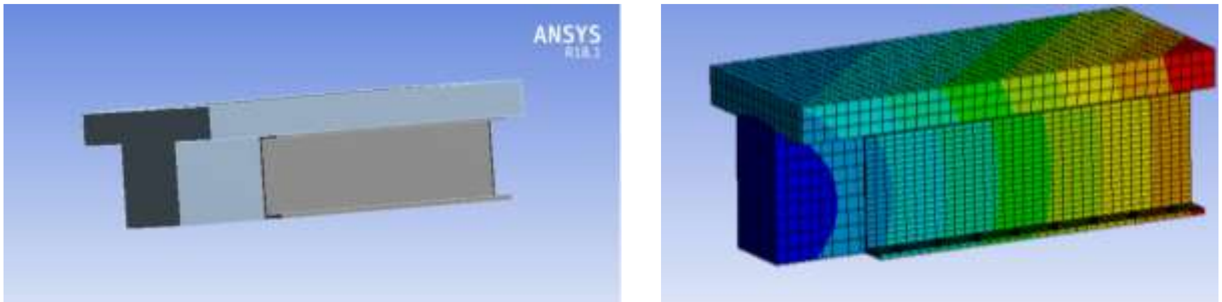

Fig-6: Specimen BCA modelled in ANSYS 18.1 and result

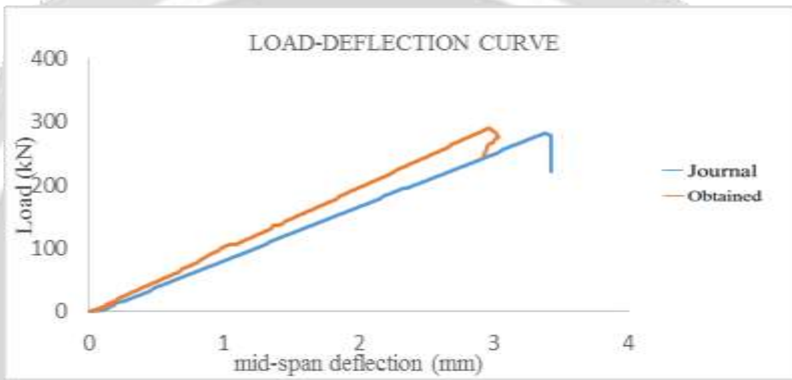

Chart-1: Comparison of Load-displacement curve obtained from ANSYS and literature

Results (chart-1) mainly indicated that there was a possible match and nearness between the values of peak load and peak displacement obtained in software and in literature. The non-coincidence between the curves may be because of the small variation in the properties used in experiment and those used in software. Although, they are coinciding at some points and are nearer in value. This indicate that the literature paper results has the possible similarity with the software results. This mainly points out that the strength enhancement in these method is an obvious factor. In case of ABAQUS CAE, the literature paper chosen had done a numerical study in ABAQUS software, in that sense, this software can create more promising results by the effective usage of the properties and the results obtained will be more accurate. For this, optimized specimens in which the flexural strength was higher is chosen. Two specimen were noted in this paper and set for the modelling in ABAQUS CAE 2017. The model included concrete, reinforcements, steel channel, cohesive layer and bolts (Fig 7). The material properties are adopted same as that of literature. The boundary condition is set as bottom support hinged and top support in which static loading condition is provided.

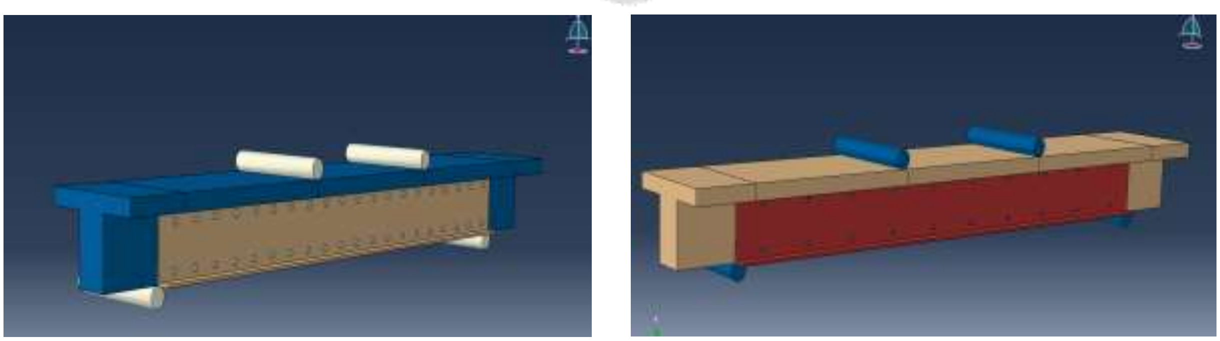

Fig-7: (a) Model BCBAO2 **Fig-7:(**b) Model BCBA04

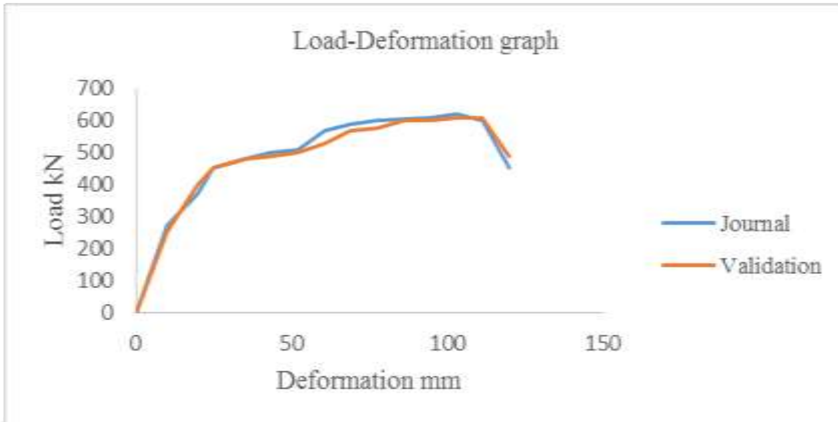

Chart-2: Comparison of Load displacement graph from software and journal

Since the model was fully modelled in same software as of the literature, the results curves also showed possible coincidence and nearness (chart-2). This made clear that this method is an effective method for retrofitting in the sense that it can create a major impact in the strength enhancement. By validating in both finite element software, it can be concluded that this paper is valid and these software can be effectively used for the study of these type of materials. Although comparing to ANSYS, ABAQUS needs more acquaintance, it reveals the better behavior of material in terms of damage.

5.2 STUDY ON USE OF LRS-FRP MATERIALS

All types of FRP are studied in recent years. What is remaining is LRS- FRPs which is commonly studied as column confining material. Large rupture strain material are preferred because, other FRPs when used have the chances of pre-mature de-bonding and rupture. LRS- FRP have the capacity to withstand high deformation because of their large rupture strain. These materials include (PET) Poly Ethylene Terephthalate materials [31]. They are mainly cost effective and moreover sustainable to use. Although there are no research coverage in this area in application for beams, it was studied in column in wrapped schemes. It is either used as strap or as sheet. In the case of columns studied by using these materials, it showed that, the confining ability and ability to undergo large deformation delays the failure in them and the seismic behavior too shown enhancement in strength and energy dissipation by placing one or more layers of material.

As a comparative study with external steel bonding, a conventional RC beam with M20 mix design is studied, in which PET laminates are externally bonded on the tension face of the beam. The properties adopted for PET-FRP are shown in table 1 and all other components of concrete and reinforcement are of M20 and Fe 415. For the effective comparison with the steel external reinforcement, a specimen with two layer of PET with standard thickness (used in previous researches) is studied under cyclic loading in software to know the extent to which the load can be taken by the beam [33].

A simple model is created with standard beam mold dimensions 150 x 150x 750 mm (fig-8). By leaving the 100mm distance from both sides of bottom face for support, (assumed distance) the PET-FRP layer of 0.8mm thickness is placed by using epoxy adhesive surfaces. In the sense that most of studied used 2 layer of PET for effectiveness, here the model is created with 2 layer of PET-FRP with epoxy adhesive layer surface defined (fig-9).

Table 1: Properties of PET-FRP

Density (kg/m^3)	Young's Modulus (M Pa)	Poisson's Ratio	Tensile strength(M Pa)
1350	10000	0.2	740

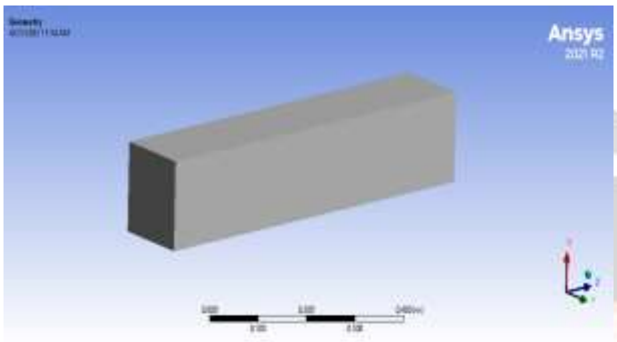

Fig-8: Model of beam with FRP

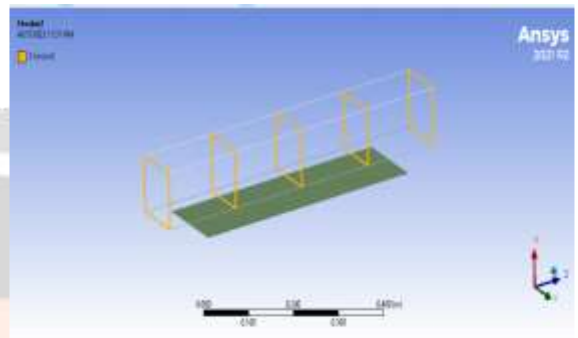

Fig-9: Model showing the FRP and adhesive surface

Boundary conditions provided are one bottom end hinged and other end with roller support, as that of simple supported and displacement controlled cyclic loading is provided for the beam. The load history provided here is Uttarkashi Earthquake data of India with 7.6 magnitude obtained from COSMOS (Chart-3).

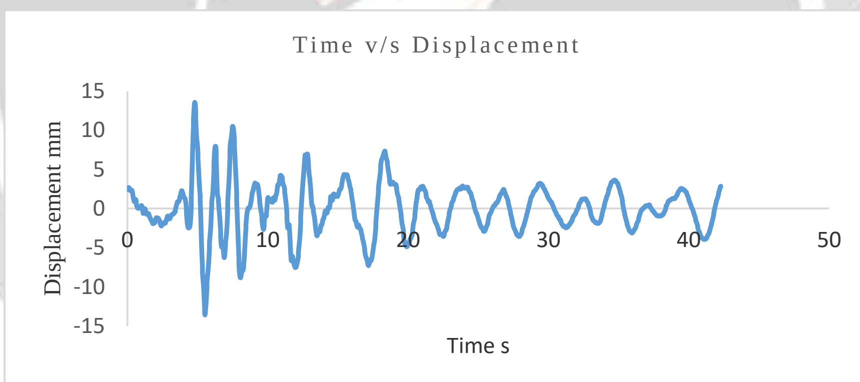

Chart-3: Time Displacement graph of Uttarkashi earthquake, India

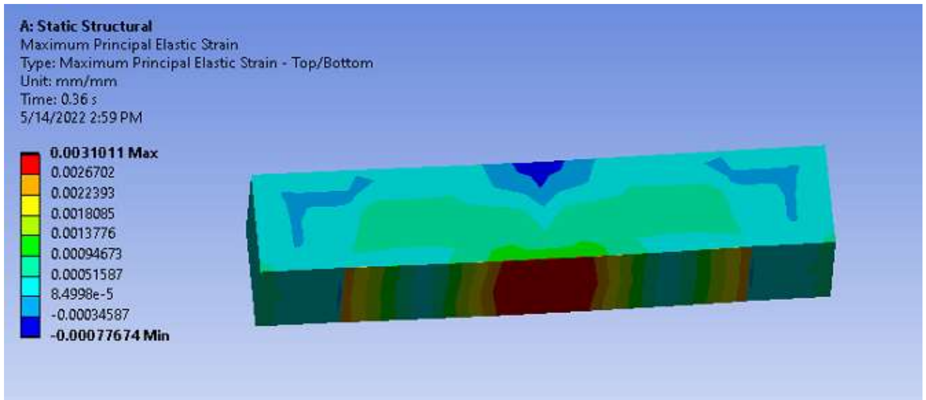

Fig-10: Maximum principal strain of PET-FRP bonded RC beam

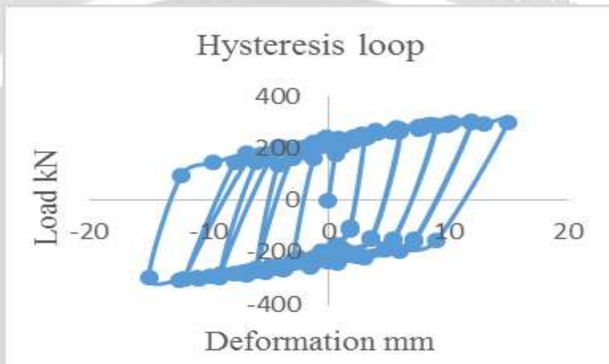

Chart-4: Hysteresis loop of beam with PET-FRP

The result of this analysis gave a hysteresis loop by using concrete bilinear isotropic hardening material property (fig-10). It is seen that, in accordance with the time, the strain capacity of FRP laminate is considerably high. The ductility capacity of the beam under cyclic load is an important factor for measuring structural response. The hysteresis loop (chart-4) shows that the small displacement has no considerable effect on it, but when the displacement is high, it has a significant effect. That is because of intense pinching at the end of loading. The large gradual increase in loading and unloading will result in deterioration. The load carrying capacity indicated in the hysteresis loop is higher in comparison with the normal beam. Even though the load carrying capacities are not as that of steel reinforcement, the effective usage will be by using LRS-FRP materials. Because, they can withstand the load to some extend in accordance with the increase in number of layers, length, depth and arrangement of LRS-FRPs.

6. CONCLUSION

This paper reviews various literature on external bonding of steel and FRP materials on the RC beams. Most of the studies prove that the use of FRP laminates on tension and shear faces have considerable enhancement in flexural and shear capacity. The conclusion drawn from the study is,

- Various ways of strengthening by using FRP are studied in detail. Many anchorage techniques are effective in eliminating de-bonding failure. However, the de-bonding effect in FRPs are yet to be studied in detail. New anchoring technique is a major requirement, which should be easy to install and cost effective. Anchoring technique mentioned in [23] are worth to be used in upcoming studies which is effective in eliminating de-bonding.
- External steel bonding can enhance the shear and flexural capacity and have the capacity of withstanding seismic loads. The external steel bonding on RC beam is validated by using two software and hence proven to be a better technique. So, this technique have the major effect in seismic retrofitting field.

- LRS-FRP laminates such as PET are studied which can withstand the large strain. Thus the flexural capacity increase is noted. Along with these laminates which is more sustainable, a good anchorage technique can be adopted which can replace the research gap of [24, 29]

7. ACKNOWLEDGEMENT

The satisfaction of completing my review paper would be incomplete without expressing my gratitude to many people who had held out their helping hands and made this possible. I would like to thank our college Vedavyasa Institute of Technology, our respected Principal, department and guide for providing all the facilities and atmosphere.

8. REFERENCES

[1] S.T Smith; J.G Teng, FRP-strengthened RC beams. I: Review of de-bonding strength models, 24(4), 385–395. doi:10.1016/s0141-0296(01)00105-5

[2] Ahmed Khalifa, Antonio Nanni, Tarek Alkhrdaji, Aramid fiber reinforced polymer for shear strengthening of RC beams, Second international conference on advances in structural engineering, Korea, Volume 1

[3] S. Altin, O Anil, M E Kara, Improving shear capacity of existing RC beams using external bonding of steel plates, Engineering structure 27(5) (2005) 781-791

[4] N. Kishi, G. Zhang, H Mikhami, Numerical cracking and de-bonding analysis of beams reinforced with FRP sheets, J. Composite construct.9(6)(2005) 507-514

[5] Yong Zhu, RKL Su. Seismic behavior of strengthened reinforced concrete coupling beams by bolted steel plates, Part 1: Experimental study, Structural Engineering & Mechanics

[6] Amer M Ibrahim, Mohammed Sh. Mahmood, Finite element modeling of reinforced concrete beams strengthened with FRP laminates, European journal of scientific research Vol 30 No.4 (2009)

[7] Md. Habibur Rahman, Ehsan Ahmed, Noor Hasan, Use of carbon fiber laminates for strengthening reinforced concrete beams, International journal of civil and structural engineering,Volume 2, No.1, 2011

[8] Thomas H Kang, Joe Howell, Sanghee kim and Dong Joo Jee, State of an review on de-bonding failures of FRP laminates externally adhered to concrete, International Journal concrete structures and materials, 6, pages123–134 (2012)

[9] Stephen V. Grelle and Lesley H. Sneed, Review of Anchorage systems for externally bonded FRP laminates, International journal of concrete structures and materials 7, 17-33 (2013)

[10] Li, Ling zhi, New partial interaction models for bolted side plated reinforced concrete beams, ACI (2013)

[11] Hawileh, R.; Abdalla, J.A.; Naser, M.Z.; Tanarslan, M, Finite element modeling of shear deficient RC beams strengthened with NSM CFRP rods under cyclic loading. Spec. Publ. 2015,

[12] Mohammed Said, Maher A Adam, Ahmed A Mahmoud, Ali S Shanour, Experimental and analytical shear evaluation of concrete beams reinforced with glass fiber reinforced polymers bars, Construction and building materials 102 (2016) 574-591

[13] Dawei Zhang, Yuxi Zhao, Wei Liang Jin, Tamon Ueda , Effect of PET Wrapping on shear performance of corroded reinforcement concrete columns, International conference on the durability of concrete structures 2016

[14] Ling-Zhi Li, Chang-Jiu Jiang, Bo-Zhou, Zhou-Dao Lu, Shear strengthening of fire damaged reinforced concrete beams using bolted-side plating, Procedia Engineering 210 (2017) 186-195

[15] Li, L.Z.; Jiang, C.J.; Su, R.K.L.; Lo, S.H, A piecewise linear transverse shear transfer model for bolted side-plated beams, Struct. Eng. Mech. 2017

[16] Z.W. Shan, R.K.L. Su, Flexural capacity model for RC beams strengthened with bolted side-plates incorporating both partial longitudinal and transverse interactions, Engineering Structures 168 (2018) 44-57

[17] L.Z. Li, Z.I. Wu, J.T. Yu, X. Wang, J.X. Zhang, Z.C. Lu, Numerical simulation of the shear capacity of bolted side- plated RC beams, Engineering Structures 171 (2018) 373-384

[18] Xin Liu, Zhou-Dao Lu, Ling Zhi Li, The use of bolted side plated for shear strengthening of RC beams: A Review, Sustainability 2018, 10 (12), 4658

[19] Feng Lin, Junchao Guo, Shear transfer of concrete strengthened using bolted steel plates, Construction and building materials 212 (2019) 109-120

[20] Ling- Zhi Li, Yi Luo, To investigate the flexural performance of BSP RC beams with buckling restraining, ACI Structural Journal, 2019

[21] Xu-Yang cao, De- Cheng Feng, Gang Wu, Seismic performance of RC frame building using precast bolt connected steel plate reinforced concrete frame braces, Engineering Structures 195 (2019) 382-399

[22] R A Hawileh, H A Musto, J A Adballa, M Z Nazer, Finite element modeling of reinforced concrete beams externally strengthened with side-bonded FRP laminates, Composites Part B 173(2019) 106952
[23] Harsh Casturi, CH Hanumantha Rao, Analysis of composite hollow RC beam strengthened with mild steel section, Material today: Proceedings 2020
[24] Cheng Yuan, Wensu Chen, Thong M. Pham , New epoxy anchor for better bonding between FRP sheets and concrete, Construction and building materials 248 (2020) 1186328
[25] Armin Maddah, Ali Golafshar, Mohammed Hossein saghafi, 3D RC beam column joints retrofitted by joint enlargement using steel angles and post tensioned bolts, Engineering structures 220 (2020) 110975,
[26] Ramin Tahaee, Masoud Soltani, Morteza Nikooravesh , Twin confinement effects of FRP and steel bar on cyclic compressive behavior of concrete, Construction and building materials 304 (2021) 124561
[27] Hafedh Abdullah Yaslam Al mashgari, Farzad Hejazi, Flexural behavior of corroded reinforced concrete beams retrofitted using CFRP rods and anchor bolts, Structures 29 (2021) 1819-1827
[28] Ranjith kumar M, Usha Priya B.T, Punitha Kumar A, Lateral torsional buckling of steel beams strengthened by steel plate, Materials Today 2021
[29] Jing Zhang, Yong Xu, Zhiheng Mai, Wenlong Lv, Flexural performance of RC T- beams strengthened with external double steel channel, Journal of Building Engineering 42(2021) 102453
[30] Cheng Yuan, Wensu Chen, Thong M. Pham, Hong Hao, Experimental and analytical study of flexural behavior of BFRP sheets strengthened RC beams with new epoxy anchors, Engineering structures 241(2021) 112441
[31] Jianhui Si, Jiebin Chen, Shixiong Qiu , Finite element analysis on eccentric compression of reinforced concrete columns strengthened by Pre-stressed polyethylene terephthalate straps and angle steel, Advances in structural engineering, Vol 0(0) 1-16
[32] Mohammed said, Ali S. Shanour, TS Mustafa, Ahmed H Abdel kareem, Experimental flexural performance of concrete beams reinforced with an innovative hybrid bars, Engineering structures 226 (2021) 111348
[33] AliSaribiyik, BasselAbodan, Muhammed TalhaBalci, Experimental study on shear strengthening of RC beams with Basalt fiber strips using different wrapping methods, Engineering science and technology Volume 24, Issue 1, February 2021, Pages 192-204