FLEXURAL RETROFITTING OF RC BEAMS BY PROVIDING ELASTIC SPRING AT THE SOFFIT OF THE BEAM

K. Rangarajan[1], S. Kothandaraman[2]
[1]M Tech., Structural Engineering, [2]Professor,
Department of Civil Engineering, Pondicherry Engineering College, Puducherry, India

ABSTRACT

Strengthening of the existing beams provide a sustainable solution by extending the usefulness and life of the structure. The need for strengthening may be due to one or more number of reasons. Demolition of an existing structure is always least preferred due to compelling sustainable practices. Various techniques and methods are adopted for strengthening of flexural members, depending upon the exigencies of the situation, cost involved in repairing, facilities and ease of execution of the method available at the given location and the discretion of the engineer. Some of the popular and often resorted to techniques for strengthening of beams are plate bonding, providing external FRP lamination, wrapping the beam in FRP Jacket, external prestressing, introduction of additional support, external reinforcement etc.

Providing an elastic spring support at the soffit of the beam is introduced as an innovative way for strengthening of discontinuous beams. Also, it can be an efficient retrofitting tool for a sustainable built environment. The advantages offered by providing the proposed elastic spring by this technique are enhancement of flexural rigidity of the member at critical locations and also in reduction of effective bending moment and shear force on the member. The structural efficiency achieved by strengthening is high to the tune of about four times the flexural capacity of the simply supported span and the control in deflection achieved is also 5 times.

Index Terms- External Truss, Flexural retrofitting, Strengthening, Trussed Beam

I. INTRODUCTION

Sustainibility is the ability to be maintained or kept going on at a certain rate or level - as an action or process. It is the ability of a system to adopt techniques - which allows continued reuse for its viability - in order to avoid depletion of natural resources to maintain ecological balance. From this, it is clear that the essentials for sustainability are

i. avoidance of depletion of resources and
ii. Continued reuse of system for viability.

From the structural analyser's view point, the above ideals can be achieved through enhancing the structural efficiency of structures. On the basis of structural efficiency, structures or members of structures may be classified as

a) Uniform stress forms and
b) Variable stress forms.

In flexural members - being of variable stress forms – the intensity of stress varies in magnitude across its cross sections from tension at one extreme fibre to compression at the other extreme fibre of each cross section. Also, there may be variation in magnitude of stresses along the length of the member. Due to these reasons, they have lesser structural efficiency. So, always there is scope for improvement in their performance. The improvement provided to the structure or member is known as strengthening. Use of techniques or addition of members or elements to an already existing member or structure is retrofitting. Various methods of retrofit or strengthening are devised on the objective of obtaining enhanced performance from the structure or for increasing the structural efficiency.

Methods adopted to enhance performance may be classified as

Active strengthening and

Passive strengthening.

In active strengthening, the properties or the parameters of the members which will provide enhanced response to the imposed actions are actually improved.

On the other hand in passive strengthening, the member is efficiently utilized, so that it may be suitably modified in such a manner that with its original strength itself the member is made capable to safely and satisfactorily offer response to the imposed actions.

Of the several available methods of retrofit, like section enlargement, section addition, plate bonding, external prestressing, external reinforcement, support addition, etc., it is proposed to suggest a modified method of support addition as a sustainable strengthening retrofit, which is a passive method. This paper provides the analysis of enhancement of flexural load carrying capacity and reduction in the deflection on a simply supported beam under uniformly distributed load, while retrofitted with a truss at its soffit.

II. NEED FOR STRENGTHENING OF BEAMS

Structures or members of structures may lose their ability to provide satisfactory performance, with passage of time. The reasons for this may be one or a combination of several reasons. The reasons may be

i. Change in user behaviour – causing changed loading conditions or modified load intensities.

ii. Change in user expectations – requiring enhanced serviceability requirements of reduced deflections, vibrations, noise, etc. and or compliance to revised or modified codal provisions.

iii. Due to passage of time, a set of or a series of phenomena manifest themselves, even when there are no changes in user behaviour or expectations.

iv. Due to environmental action. Environmental action imposes significant alterations on the characteristics and behaviour of the material constituents, elements, members and the structure as a whole or part. They can cause deterioration and or degradation of the constituents either wholly or partly, leading to impediments in the strength, safety and serviceability of structures. Earthquakes are environmental action which can set in dynamic actions which affect the performance of structures.

To replace a structure, wholly or partially is not always desirable nor is it practicable or feasible. Discarding an existing structure and resorting for replacement is least desirable due to compelling sustainability practices and procedures and also due to the adverse environmental impact. Also, the high cost of replacement and the non-availability of service during the period of replacement have deep social ramifications.

Due to all these reasons, strengthening is the most preferred solution for making structures safe and effective in such situations.

III. BACKGROUND FOR THE STUDY

Since 1960s epoxy bonded steel plates have been used in Europe and other places for flexural retrofit of members. Reference [31] conducted studies on beams strengthened by steel plate bonding. The method adopted attaching steel plates by epoxy bonding to the surface of beams. Steel plates have a durability problem unique to this application. Corrosion may occur along the adhesive interface, which affects the bond at the steel plate concrete structure interface and is difficult to monitor during routine inspections. [11]. Occurrence of undesirable shear failures, difficulty in handling heavy steel plates, corrosion of steel plates and the need for butt joint systems as a result of limited workable lengths are some of the problems associated with this method. [18].

This led to the evolution of use of Fibre Reinforced Polymer (FRP) materials for external plate bonding. FRP materials as thin laminates or fabrics would appear to offer an ideal alternative to steel plates. Reference [21] of Switzerland was the pioneer in studying the use of FRP materials for strengthening of flexure members. Use of Carbon FRP (CFRP) has increased the maximum load upto 23% for retrofit in shear and by 7% to 33% for retrofit in flexure [24]. They generally have high strength to weight and stiffness to weight ratios and are quite inert chemically, offering significant potential for lightweight, cost effective and durable retrofit.[22], [3]. However, retrofitting using FRP is also vulnerable to undesirable brittle failures due to a large mismatch in the tensile strength and stiffness with that of concrete. [13].The long-term durability of CFRP structural systems applied to reinforced-concrete (RC) highway bridges is a function of the system bond behaviour over time. The sustained structural load performance of strengthened bridges depends on the CFRP laminates remaining 100 % bonded to concrete bridge members. CFRP plates with de-laminations can potentially produce deterioration in bridge performance [27].The load performance of CFRP-strengthened RC highway bridges is a function of the bond-interface behaviour in the CFRP laminate–epoxy–concrete structural system.[9]. Nowadays, Externally Bonded-FRP (EB-FRP) applications represent a well-established technique for the rehabilitation of existing RC structures, considered by international codes and guidelines as a proper and valid option for structural retrofit. Although FRP systems are extensively used, they have some drawbacks, such as high cost, low fire resistance, low environmental sustainability, low compatibility with traditional building materials.[14]. So far, in spite of the limitations in the methods, such as high cost, requirement of high skills of execution, undesirable debonding failures, etc., the method remains popular for strengthening and retrofit of flexure members, particularly beams.

[4, 5, 6] reported that the flexural capacity of RC beams strengthened with external reinforcement was increased upto 85%. The reinforcement was provided to the sides of the beam at the level of embedded reinforcement. Deflectors, yokes and specially rendered end anchorages were required. Reference [32] have studied the enhancement of strength of RC beams with external reinforcement at its soffit and enumerated a 140% enhancement in strength.

Attachment of truss has been reported to provide 146% enhancement in ultimate moment capacity and 2.5 to 2.7 times in load capacity, by attaching truss to the sides of the beam below the neutral axis. [17]. Two point loading has been used for the above studies.

In the present study, it is proposed to examine the strength enhancement and reduction in deflection of a simply supported reinforced concrete (RC) beam subjected to uniformly distributed load, by attaching the truss at the soffit of the beam.

IV. ANALYSIS

The performance requirements for a flexure member are primarily its strength and serviceability. The strength of the member is its moment capacity and shear capacity. The serviceability requirement is primarily the control of its limit of deflection. The enhancement in efficiency achieved by strengthening can hence be compared to the moment capacity and deflection of the simply supported beam.

It is proposed to study the effect of the introduction of a spring support to strengthen the beam, on the variation achieved in the moments occurring throughout the beam and the control of deflection.

If the stiffness of the spring – the proposed additional support – is set to zero, then the maximum bending moment on the beam is $\frac{wl^2}{8}$.

The maximum deflection of the beam is $\frac{5wl^4}{384EI}$.

Both occurs at $\frac{l}{2}$, i.e. at centre of the beam. A spring of zero stiffness means no support as shown below in Fig.(1 a).

On the other hand, if the stiffness of the spring is set to infinity, a moment of $\frac{wl^2}{32}$ is induced over the new support and the maximum span moment would be $\frac{9wl^2}{512}$ which would occur at $\frac{3}{16}l$ from extreme supports. A spring of infinite stiffness means a rigid support as shown below in Fig.(1 b).

Thus by varying the stiffness of the spring from zero to infinity, the span moment can be reduced from $\frac{wl^2}{8}$ to $\frac{9wl^2}{512}$. However the reduced span moment is associated with a support moment of $\frac{wl^2}{32}$ at the spring location.

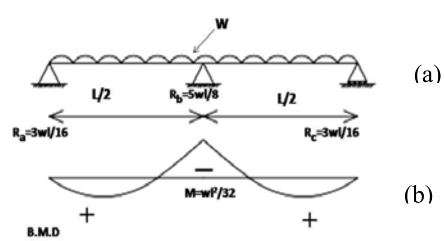

Fig.1 A rigid support introduced at the centre of the Simply Supported Beam

If the stiffness of spring is set to $\frac{192EI}{l^3}$, then the support moment at the spring location is entirely released. The resulting bending moment diagram appears as if the beam is composed of two discontinuous spans each of $\frac{l}{2}$ and the maximum span moment is only $\frac{wl^2}{32}$ as shown in Fig. 2. The maximum deflection on the beam is only $\frac{wl^4}{384EI}$. The strengthening achieved is four times in flexure, because the maximum span moment has reduced by one fourth. Also the reduction in deflection is five times. The elastic spring support of varying spring stiffness can be physically provided by a truss as shown in (Fig. 2 e).

Thus, the uniqueness in this method is that the bending moment at an intermediate point on the simply supported span has been totally reduced to zero.

Generally, the conditions required for the moment at a point or location on a beam to be totally released or to be reduced to zero are, that there should either be a discontinuity or a hinge. Also, the moment along the span will be reduced to zero at the point of inflection.

However, in this study it is demonstrated that without any of these conditions the moment at an intermediate point on the span can be reduced to zero.

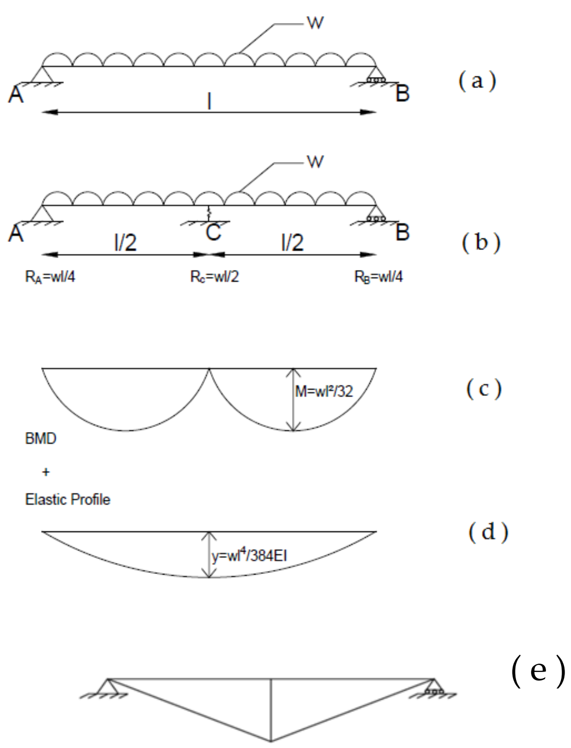

Fig. 2 An elastic support introduced at the centre of the Beam

By varying the stiffness of the spring, the moment at spring support location and span moment can be modified as per situation or necessity. Thus, this method automatically offers the best solution in the case where a hinge has formed or failure has occurred on the beam. By introducing a spring of appropriate stiffness, the beam can be strengthened for continued use, even under enhanced loading.

From the conditions of compatibility, the stiffness of the spring is derived as given below.

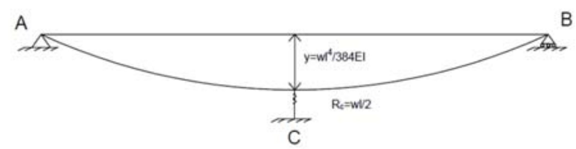

Fig.3. Compatibility condition for the spring stiffness

The moment at any point X, x away from support A is given by ,

$$M_X = R_A x - \frac{wx^2}{2} \quad (1)$$

For the moment to be 0 at centre $x = \frac{l}{2}$ i.e. at

$M_x = R_A(\frac{l}{2}) - \frac{w(\frac{l}{2})^2}{2} = 0$. So, $R_A = \frac{wl}{4}$

So, the thrust on the new support at C is

$$R_C = \frac{wl}{2} \quad (2)$$

The deflection at any point X, x away from support A can be expressed as

$$y = \frac{w(4lx^3 - 2x^4 + l^3 - 3l^3 x)}{48EI} \quad (3)$$

The deflection at $\frac{l}{2}$ centre C, away from support A is

$$y = \frac{wl^4}{384EI} \quad (4)$$

The max shear on the beam is $\frac{wl}{4}$ at supports. The max span moment on the beam is $\frac{wl^2}{32}$ at $\frac{l}{4}$ from supports.

Thus it can be seen that, the maximum moment on the span has reduced from $\frac{wl^2}{8}$ for the simply supported span to $\frac{wl^2}{32}$ for the strengthened span, ie., the flexural strength has been enhanced 4 times.

Also, the deflection has reduced from $\frac{5wl^4}{384EI}$ for the simply supported span to $\frac{wl^4}{384EI}$ for the strengthened span – a reduction to one fifth.

Thus, the yield required at the centre of span is $\frac{wl^4}{384EI}$ as shown in Fig. 3 and the force in the spring is $\frac{wl}{2}$.

So, the stiffness of spring required to produce the yield is $\frac{wl}{2} / \frac{wl^4}{384EI} = \frac{192EI}{l^3}$. (5)

It may be noted that the stiffness of spring is independent of the load imposed on the beam and is only a function of the mechanical properties of the beam, namely the span l, and flexural stiffness (EI).

The area of strut required is easily found out from the compatibility conditions. Applying the compatibility condition of displacement at support point C as

$$y = \frac{wl^4}{384EI} = \Delta_{Strut} + \Delta_{TieVertical} \quad (6)$$

where Δ_{Strut} is the contraction in the strut and $\Delta_{TieVertical}$ is the elongation in the tie resolved vertically.

$$A_{Truss} = \frac{48(EI)_{Beam}}{l^2 E_{Truss}}\left(2\tan\theta + \frac{1}{(\sin^2\theta\cos\theta}\right) \quad (7)$$

The area of truss is a function of the flexural stiffness of beam $(EI)_{Beam}$, the elastic modulus of truss E_{Truss}, the span l, and the angle of tie θ. For a given beam, the only variable would be the θ.

A plot of the area of truss required for a single strut truss for a given span at different angles of truss is provided in Fig. 5.

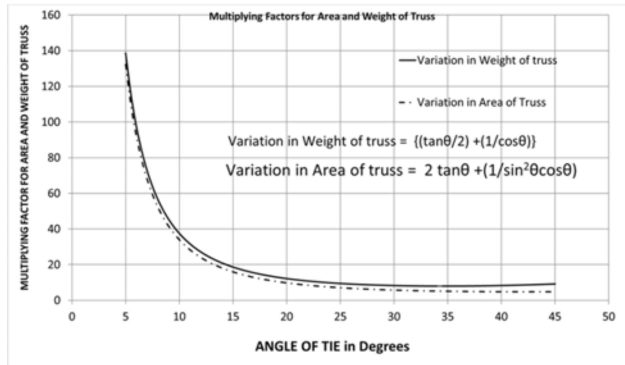

Fig.5 Area required for different angles of tie – Single Strut

Table 1 Comparison of Area of Reinforcement and Area of Truss members

b – Breadth, D – Overall Depth, A_{st} – Area of steel reinforcement, A – Area of cross section of tie/strut

Span (m)	Beam cross section b × D (mm)	A_{st} (mm^2)	A_{st} (%)	Capacity of Beam		Details of Retrofit						
						θ = 35°		θ = 20°			Effect of Retrofit	
				Moment (kNm)	Load (kN/m)	A (mm^2)	$\frac{A}{A_{st}}$	A (mm^2)	$\frac{A}{A_{st}}$	$\frac{A_{@20°}}{A_{@35°}}$	Load (kN/m)	Enhancement
5	150 × 250	339	1.01	22.64	7.25	269	0.79	517	1.53	1.92	28.99	Four times
10	250 × 500	1257	1.07	174.36	13.95	928	0.74	1784	1.41	1.92	55.80	
15	375 × 750	3078	1.15	641.02	22.79	2137	0.69	4107	1.33	1.92	91.17	
20	500 × 1000	5655	1.17	1579.10	31.58	3848	0.68	7397	1.31	1.92	126.33	

Note: Characteristic compressive strength of concrete is taken as 25MPa and for steel, characteristic tensile strength of steel is taken as 415 MPa.

V. CONCLUSION

From the conduct of the above analysis, the following inferences are drawn.

1. It is technologically feasible to control the maximum bending moment and deflection in simply supported beam elements to any desired level by attaching a single or multiple strut truss at the soffit of the beam.

2. The stiffness of the truss element - which acts as an elastically yielding support - is independent of the loading. It is a function of the stiffness of the beam i.e. $\frac{192EI}{l^3}$ in the case of single strut truss.

3. Using a single strut truss can enhance the flexural load carrying capacity of the existing beam to 4 times. Also the maximum deflection is reduced by 5 times. This scale of enhancement of performance is very good compared to those provided by other methods. The shear force is also reduced by half.

4. However, caution is to be exercised while designing the stiffness of the spring, because if the spring is stiffer than required, rigidity of the support imposes restrain to rotation at the spring support, thereby inducing a hogging moment at that support. Instead, it would always be ideal to have a flexible spring, which has lesser than required stiffness. This will economise the truss, though some residual sagging moment will prevail at the support location.

5. The area / weight of truss required for a given beam depends on the angle of tie. A specific angle of tie provides the most economic weight of truss. However, at angles of tie less than about 10^0 the area/ weight requirement will increase very steeply (Figs. 5,6,7,8,9 & 10), because of higher axial tension in tie members. Angle of tie between 10^0 and 35^0 provide reasonable and economic area / weight of truss. Further increase in the angle of tie beyond about 35^0 doesn't provide any economic advantage.

6. This paper doesn't discuss about two more structural advantages that are also derived out of attaching the truss to the soffit of the beam.

i. The horizontal component of the tie force will bring an axial thrust on to the beam section and

ii. The tie member has to be suitably anchored near the support region of the beam. The beam section will be subjected to a uniform hogging bending moment due to the eccentricity of the horizontal component of tie force because of the attachment of tie away from the neutral axis of the beam. Hence the load intensity on the beam can be further increased without endangering the strength of the beam.

7. It is proposed to experimentally study the response under ud load on attaching a truss at the soffit of a beam, in terms of increase in load carrying capacity and reduction in deflection. The findings of the study will further be published.

References

[1] Al-Mahaidi, R. 2002, Strength Assessment & FRP Strengthening of Concrete Bridges. in Short course in Use of FRP Composites in Retrofitting of Concrete Structures, Melbourne: Monash University.

[2] Ashour AF, El-Refaie S.A., and Garrity, S.W., 2004, Flexural strengthening of RC continuous beams using CFRP laminates. Cement & Concrete Composites.; 26:765-775.

[3] Buyukozturk, O., and Hearing, B. 1998.Failure behavior of precracked concrete beams with FRP. *J. Compos. Constr.,* 2(3), 138– 144.

[4] Cairns J and Zhao Z, 1993, Behaviour of Concrete Beams with exposed reinforcements, ProcInstCiv Eng. Struct Build;99:141-54.

[5] Cairns J, Rafeeqi SFA, 1997, Behaviour of RC beams strengthened by external unbounded reinforcement, Constr Build Master; 11(5-6):309-17

[6] Cairns J, Rafeeqi SFA, 2002, Analysis of RC beams strengthened by external unbonded reinforcement, Mag Concr Res;54(2):141-53.

[7] Chen, J.F. and J.G. Teng, 2001, Anchorage Strength Models for FRP and Steel Plates Bonded to Concrete, Journal of Structural Engineering ASCE, 127(7).

[8] Chen, W.F. and L. Duan, 2000, Bridge Engineering Handbook, Boca Raton: CRC Press.

[9] Crawford, K C., 2016, NDT evaluation of long-term bond durability of CFRP-structural systems applied to RC highway bridges, Int J AdvStructEng DOI 10.1007/s40091-016-0120-2.

[10] Draft Guidelines for retrofit of concrete structures, 1999 – Japan Society of Civil Engineering.

[11] Ehsani, Tom Norris and Hamid Saadatmanesh (1997), Shear and Flexural Strengthening of R?C Beams with Carbon Fiber Sheets, Journal of Structural Engineering.

[12] Esfahani, M. R., Kianoush, M.R., and Tajari, A.R., 2007, Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. Engineering structures, 29: 2428-2444

[13] Farshid Jandaghi Alaee and Bushan Lal Karihaloo , 2003, Retrofitting of RC Beams with CARDIFRC, Journal of Composites for Construction

[14] Francesco Bencardino and Antonio Condello, 2016, Innovative solution to retrofit RC members: Inhibiting Repairing-Strengthening (IRS) Construction and Building Materials, DOI :10.1016/j.conbuildmat. 2016.05.053.

[15] Garden, H.N., and Hollaway, L.C., 1998, An Experimental Study of the Influence of Plate End Anchorage of Carbon Fiber Composite Plates used to Strengthen Reinforced Concrete Beams. Composite Structures., 42, 2, 175-88.

[16] Hassan. T and Rizkalla.S., (2001), Strengthening of Bridge Slabs with FRP systems, Structural Faults and Repair Conference Proceedings, London, United Kingdom

[17] Hemaanitha. R and Kothandaraman. S, (2016), Strengthening Of RC Beams Retrofitted With External Truss – An Experimental Study, Asian Journal Of Civil Engineering (BHRC) Vol. 17, No. 8, Pages 1087-1098.

[18] Hussain, M., Sharif, A., Basunbul, I.A., Baluch, M.H., AlSulaimani, G. J., (1995), Flexural Behaviour of Pre-cracked RC Beams Strengthened Externally by Steel Plates, ACI Structural Journal, 92(1), 14-22

[19] Huy Pham and Riadh Al-Mahaidi, 2004, Flexural Retrofitting of Concrete Bridge Beams Using CFRP Fabrics, https://www.researchgate.net /publication / 266277082

[20] IAEE Manual, 2004, National Information Centre for Earthquake Engineering, IIT, Kanpur

[21] Meier, U. (1987). Bridge repair with high performance composite materials. Material and Technik, 15: 125 – 128.

[22] Nanni, A. 1995. Concrete repair with externally bonded FRP reinforcement: examples from Japan.'' *J. Concr. Int.*, 97, 22–26.

[23] National Disaster Management Guidelines (NDMG), 2014 – Seismic Retrofitting of Deficient Buildings and Structures - National Disaster Management Authority, Government of India

[24] Obaidat, Y.T., Heyden, S., Dahlblom, O., Abu-Farsakh, G., and Abdel-Jawad, 2010, Retrofitting of reinforced concrete beams using composite laminates. Submitted to Construction & Building Materials.

[25] Piero Colajanni, Lidia La Mendola and Alessia Monaco, 2016, Experimental Investigation of the Shear Response of Precast Steel–Concrete Trussed Beams,Journal of Structural Engineering

[26] Shamim A. Sheikh, (2002), Performance of concrete structures retrofitted with fibre reinforced polymers, Engineering Structures 24 (2002) 869–879

[27] Shih J, Tann D, Hu C, Delpak R, Andreou E (2003) Remote sensing of air blisters in concrete-FRP bond layer using IR thermography. Int J Mater Prod Technol 19:174–187

[28] Sinha NC, (2011),Elements of Structural Analysis, NCBA,

[29] Smith, S.T., and Teng, J.G., (2002), FRP-Strengthened RC Beams I: Review of Debonding Strength Models. Engineering Structures., 24, 4, 385-95

[30] Sobuz Habibur Rahman, Ehsan Ahmed, Md. Alhaz Uddin, Noor Md. Sadiqu, 2011, Structural strengthening of RC beams externally bonded with different CFRP laminates configurations, Journal of Civil Engineering (IEB), 39 (1) 33-47.

[31] Swamy RN, Jones R, Ang TH (1982). Under and over reinforced concrete beams with glued steel plates. International Journal of Cement Composites and Lightweight Concrete, 4(1):19–32.

[32] Vasudevan and Kothandaraman,(2014), Experimental investigation on the performance of RC beams strengthened with external bars at soffit, Materials and Structures 47:1617–1631 DOI 10.1617/s11527-013-0141-2

[33] Yasmeen Taleb Obaidat, (2010), Thesis: Structural Retrofitting Of Reinforced Concrete Beams Using Carbon Fibre Reinforced Polymer, ISRN LUTVDG/TVSM--10/3070--SE (1-76) ISSN 0281-6679, LTH, Lund University, Sweden.