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A REVIEW OF BEHAVIOUR OF EXTERNALLY PRESTRESSED BEAMS

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ABSTRACT

A detailed review of available literature in external prestressing in particular to the behaviour of beams and assessment at ultimate is done. The behaviour of external post tensioning beam is different from the bonded prestressing due to the strain incompatibility condition. The effect of external tendons in either a pre-cracked beam or in a new beam (both in flexure and shear) is reviewed. Various researches parameterising the geometry of tendon profile, effect of deviator blocks, level of strain in internal passive reinforcement, loading types, effect of initial crack widths, combination of external prestressing and fibre wrapping and the increase in tendon stress at ultimate, is reviewed

Key words: External Prestressing, Tendons, Repair, Shear Capacity, Flexural Cracks, Effective Prestress.

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1. INTRODUCTION

External prestressing is a technique in which the tendons are kept outside the concrete member. The significance of external prestressing in infrastructure projects is very relevant in India, as a fast developing country. In past two decades, in India, numerous bridges were built, as part of the infrastructure development. During the same period, the various loading and design codes were also updated in line with the improved demands. External post-tensioning can be considered an effective strengthening method for bridge members, which are deteriorating due to extreme loading conditions and progressive structural aging (Aravinthan & Suntharavadivel, 2007)[1]. The number of heavy trucks and traffic volume on these bridges has risen to a level exceeding the values used at the time of their design. This resulted in usage of external prestressing as a viable alternative for retrofitting of the existing bridge and also in new segmental bridges (Manisekar et al. 2013; Tan & Ng, 1998)[14,22]

The tendons, deviators and anchorage blocks are placed inside the bridge girder so that the intended aesthetics is not changed.

Figure 1 Arrangement of external prestressing in box girder. (Courtesy VSL)

The successful usage of external prestressing, its advantages and practical constraints are discussed in detail by Suntharavadivel & Aravinthan (2005)[20]. Elisabeth et al. (1995)[9], detailed the principle, advantage and limitations of external prestressing. In the case of excessive deflection and cracks, the opposing forces from the draped tendons may not reverse the mid-span deflection by more than a fraction nor will close the wide cracks or open joints completely, after applying the additional prestress. According to them this is attributed to the higher stiffness of cracked section (Elisabeth et al. 1995)[9].

Numerous research works were carried out to understand the behaviour of beams with external prestressing. The research works were mainly aimed at the formulation of parameters, increase in stress beyond the effective prestress, prediction of ultimate stress, validation of codes, development of various analysis models, effect of external blisters, effect of draping, the prediction of strength considering the global deflection, effects in shear, behaviour of pre-cracked beams, and various numerical models to understand the behaviour.

STUDY AND REVIEW

Aravinthan & Suntharavadivel (2006, 2007)[21,1], had carried out studies in enhancing the shear capacities using model specimens, with a case study in The Tenthill Creek bridge. The bent caps were strengthened by external prestressing. While the flexural cracks will close during the external prestressing, since the shear cracks are inclined, the horizontal post-tensioning will have an effect on the behaviour of the structure. Experimentally they found that the width of the existing cracks has an influence on the behaviour and the shear capacity increases by upto 70%, with external prestressing with properly treated joints with epoxy injection.

Second Order effects are minimised if the change in eccentricity is reduced by providing more number of deviators (Harajli et al. 1999; Tan and Ng, 1998)[11,22]. In this condition, the strength and failure modes can be predicted as per Strut and Tie model. In the various experiments done by Tan and Ng (1998)[22], it is reaffirmed that reducing the concrete strength or the amount of shear reinforcement would result in the beam failing in the shear mode. When an adequate concrete strength and shear links are provided the failure will be in flexure, even though the span to depth ratio is as low as 2.5. The phenomenon of increase in stress in unbonded internal tendons almost after the yielding of un- tensioned steel lead to the formation of plastic hinge. This is not the case in external prestressing and hence there is a reduction in ductility. The research work carried out by Manisekar, R., et al. (2013)[14], on precracked beams concluded that external prestressing with draped cable profile (with deviators) has enhanced the capacity of beam by 48% in comparison to 17% by straight cables.

Through non-linear analytical model, Harajli et al.(1999)[11], has reconfirmed everything else being constant, tendons without deviators produce lower nominal flexural strength than tendons with deviators do. Providing a moderate amount of external prestressing steel leads to significant deflection recovery, smaller service load deflections, and substantial increase in the yield strength and ultimate flexural capacity of the members.

To determine the nominal moment resistance of beams prestressed with unbonded tendons, it is necessary to predict the stress in the prestressing tendons at ultimate. The stress increase Δfps in the tendons beyond the effective prestress due to external loading is member-dependent instead of being section dependent (Au and Du, 2004; Naaman and Alkhairi, 1991)[3,15]. This gives the simplified formulae for finding the ultimate tendon stress at flexural failure of prestressed concrete beams with unbonded tendons. Continuing their studies to service stage, Au et al.(2005)[4], developed a numerical model for predicting the behaviour for Unbonded Partially Prestressed Beams upto cracking of beams and yielding of steel.

An extensive study was conducted by Naaman and Alkhairi (1991) [15,16] for calculating the increase in prestress force Δfps beyond the effective prestress.

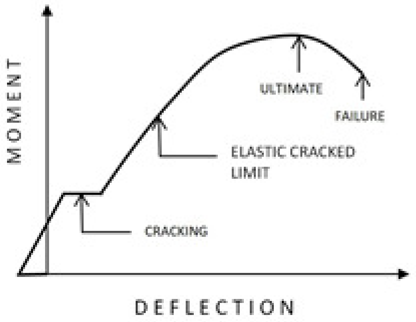

Figure 2 Schematic moment – deflection diagram for beams prestressed with unbonded tendons [11].

For the elastic uncracked section analysis, a bond reduction coefficient Ω as defined below is introduced.

$$\frac{(\Delta\varepsilon psu)m}{(\Delta\varepsilon psb)m}$$

where $(\Delta\varepsilon psu)_m$ is the strain increase in the unbonded tendons, $(\Delta\varepsilon psb)_m$ is the strain increase in the equivalent bonded tendon.

They experimentally found the values of above coefficient for various types of loading. With this the fair estimate of ultimate moment capacity can be arrived. The above values of coefficient were further checked and fine- tuned by Aparicio et al. (1996)[2], both analytically and experimentally.

In the limited works done on pre-cracked beams, (one of which is already mentioned above), significant work was carried out by Teng et al. (1996)[25], on shear strengthening. Here the shear strengthening is done by steel clamping. Experimental work was carried out for different shear reinforcement configuration such as vertical, horizontal, and combination of both and the results checked. Prestressed and non-prestressed concrete deep beams were tested to failure, strengthened, and then retested to failure for a second time. On the occurrence of the first (shear) failures, the failed shear spans of the beams were strengthened by using steel clamping units that acted as external stirrups. Once the clamping units were introduced, the internal force transfer mechanism changes and hence the shear capacity has increased. The beams were not only restored fully, but the capacity was increased more than the original beam.

A very interesting observation by him is that the presence or amount of web reinforcement does not have much effect on the strength of the clamped shear span, since the shear force is basically carried out by the clamping unit, which is designed for the full shear force.

There is a conceptual difference in usage of external prestressing for (i) As primary reinforcement in new bridge and (ii) For strengthening of existing bridge. For the case (i) above, the analysis and design is similar to the methods adopted for un-bonded post-tension type, whereas for the case (ii) above, the presence of passive reinforcement, and / or bonded prestressing force, its current state of stress make the estimation of external prestress difficult (Harajli, 1993)[10]. Another major difference from the point of serviceability limits is the extent of deformation, deflection and level of crack widths, at which the external prestressing is applied. In his detailed work on external prestressing, he has given numerous findings on the behaviour of externally prestressed beams. He found that the reduction in deflection as a result of external prestressing is expected to be about 36 percent larger for the deviated profile than for the straight profile. This has eventually deduced the fact that for a two point load model, the failure of the externally prestressed beam is close to the midspan (constant moment region) and below the load point for straight profile and deviated profile respectively. Another finding from the strain of internal reinforcement is that under the applied service loads, external prestressing resulted in significant reduction of the internal tension of passive reinforcement. This will result in the improved fatigue life of the structure.

Harajli (1993)[10] in his work has given the following formulae for finding the strain and corresponding stress, as a function of central beam deflection.

$$\Delta\varepsilon_{ps} = \frac{4e_m}{L^2}\,\delta_o$$

$$\varepsilon_{ps} = \varepsilon_{pe} + \Delta\varepsilon_{ps}$$

In the linear elastic range:

$$f_{ps} = f_{pe} + \left(\frac{4E_{ps}\,e_m}{L^2}\right)\delta_o$$

In the nonlinear range:

$$f_{ps} = F\left(\varepsilon_{ps}\right)$$

Where

L = Span length

e_m, e_s = eccentricity of external tendons at midspan and anchorage ends, respectively.

δ_o = Increase in central beam deflection with applied load after external prestressing.

f_{pe},ε_{pe} = effective prestress and effective pre strain, respectively, in external prestressing steel.

A detailed practical account of external prestressing, its usage in different types of bridges such as girder type, truss, box, solid slab is given by Daly and Witarnawan (1997)[8]. In addition to the two case studies, Condet Bridge and Kemelaka Gede Bridge both in Indonesia, authors had qualitatively given the advantages and disadvantages. While the economy, easy maintenance, least disruption to traffic during installation, non-compromise of aesthetics in particular to box girder are cited as advantages, the assessment of quality of concrete, the extent of damage and hence the quantum of additional prestress force, the location of existing reinforcement inside the concrete to install the external deviators and blisters etc. are cited as disadvantages.

Manisekar and Senthil (2006)[13], gave a comprehensive view on various studies conducted to find the stress at ultimate condition, based on the length of the plastic hinge formed. As a continuation to the above, they also investigated the effect on external prestressing in new as well as distressed beams. Here the basis of the review is attributed to the unsatisfactory performance in predicting the stress in unbonded tendons, due to the lack of evaluation of plastic hinge length.

For the case of externally prestressed beams, the compression line shift C_{shift} due to the global behaviour is found out and the modified stress as under were reported

$$S_{top} = \frac{P}{A} - \frac{P(e - C_{shift})}{Z_t}$$

$$S_{bot} = \frac{P}{A} + \frac{P(e - C_{shift})}{Z_b}$$

Where S_{top} and S_{bot} are the stresses due to external prestress in top and bottom fibre respectively. C_{shift} = shift in the position of resultant compression.

It was also reported by Senthil and Manisekar (2015)[14] that the cracks closed due to external prestressing will open only after decompression taking place, and the deflection will start occuring only after cracks opening (i.e., after decompression). The formulae for calculating the deflection of strengthened RC beams and length of plastic hinge is given.

The effect of untensioned steel in the stress behaviour of unbonded tendons were analysed by Tao and Du (1985)[24]. The combined reinforcement index "q_o", which is a ratio of area of bonded untensioned reinforcing steel to the area of the concrete is found to be an important factor for assessing the tendon stress increment at failure Δf_{ps}. The q_o depends on the depth of neutral axis and when this goes towards compression zone, the value of Δf_{ps} increases. Thus they found out that while an increase in grade of concrete, increases the Δf_{ps}, and an increase in q_o reduces the value of Δf_{ps}. The following relationship is established.

$f_{ps} = f_{pe} + (786 - 1920\, q_o)$, for $q_o \leq 0.3$, where f_{ps} is the ultimate stress in unbounded tendon.

A full scale damaged beam model, strengthened with external prestressing, to assess its flexural behaviour was carried out by Sirimontree and Teerawong (2010)[19]. The results from their tests and analytical backup showed that degradation, loss of internal prestressing force and flexural stiffness of the girder depend directly on Damage Index (DI). This term is defined as the ratio of permanent deformation and crack deformation of original undamaged girder, which is $\frac{\Delta p}{\Delta cr}$ or $\frac{\emptyset p}{\emptyset_{cr}}$. Another outcome of the test is that the significance of both unbonding and the second order effect (P- Δ effect) due to incompatibility between member deformation and external tendon profile in post-cracking or inelastic stage are very low and can be ignored. The parametric study conducted on different DI indicated that the loss of prestress, loss of flexural stiffness and level of external prestressing directly depends on DI.

Lee, Shin and Thomas (2015)[12], had done experiments on flexural strengthening of continuous beams with prestressed steel bars. The analytical predictions are almost similar to the external unbonded prestressing systems, but with the following practical advantages.

- Strengthening with steel bars requires only tightening nuts or turnbuckles without the need for hydraulic jacking equipment or room for jacking.
- it is easy to retension, monitor, and replace the posttensioning steel and anchoring nuts
- Usually the long term effects of creep and shrinkage would not be a concern because significant shortening is likely to have occurred at the time of strengthening. For the prestress loss due to steel relaxation, retensioning (retightening) is recommended after a certain period and can be easily done

- Furthermore, simple maintenance (for example, visual inspection) can be done at minimal cost.

An in-depth study carried out by Qi and Wang (2015)[17] on the effect of draped tendons on crack distribution and shear capacity gives a detailed account of behaviour of externally prestressed beam and RC beam in shear.

- Vertical component of external prestressing resists shear force directly.
- The appearance of shear diagonal crack is delayed and the propagation of critical shear crack is restrained by prestressing, resulting in a relatively larger shear cracking load and shear strength in EPC beams compared with RC beams.
- External prestressing increases the height of shear compression zone, and hence improves the shear contribution of concrete.
- Prestressing flattens the inclination of shear crack, thus increasing the contribution of stirrups.
- The outcome of this research is the coining of shear strength formula as under.

$V_u = K(V_c + V_s) + V_p$ where K is the increasing coefficient of external prestressing which is $\sqrt{\frac{fpc}{ft}} + 1$

V_p is external tendon shear contribution.

Choudhury et al. (2014)[7] in their research had found out the failure mode of beam strengthened for shear by means of a combination of FRP laminates and external prestressing. A simplified numerical model and formulation, based on the section analysis level, is developed by Andrea et al.(2007)[5]. This method is based on the observation that beams with the same structural configuration, constraints, tendon path, and type of loading, have a similar spatial distribution of curvature at collapse, and no large differences occur by varying other parameters, such as cross-section shape and depth, span length, and reinforcing bar quantity, within the range of practical interest.

Tests on continuous beams, strengthened for positive and negative moment locations were carried out by Tan and Tjandra (2007)[23]. The strengthening was carried out by short cables over critical sections instead of long continuous draped cables. This led to more ductile behaviour compared to the continuous cables. Design charts were developed based on the parametric study conducted, with different "Strengthening Ratio" (S.R) and "Global Prestressing Index" (Xc)

S.R = $\frac{P_{u,s}}{P_{u,o}}$, where $P_{u,s}$ is the ultimate load- carrying capacity of the strengthened beam and $P_{u,o}$ is the capacity before strengthening.

$X_c = X_m + 1/3\ X_s$, where X_m and X_s are the moment capacity at positive and negative regions.

A numerical study was conducted by Ali et al.(2013)[6], on external prestressing beams, considers the effect of friction in deviator blocks. The response of the beam upto the elastic limit based on the deformation compatibility and friction at deviator location was proposed. The strain induced in the concrete at the level of the cable varies with the bending moment, while the strain in the external cable is constant between the deviator blocks. A parametric study with different friction coefficient on deviator such as 0.2, 0.25 and 0.3 is considered for developing the algorithm to calculate the incremental strain at the level of deviators.

3. SUMMARY

It is observed that the various review that the external prestressing is definitely a very viable and practical option for strengthening of the existing bridge. The calculation of stress in the bonded tendons is simple since the strain compatibility equations are applicable. But for the unbonded external prestressing tendons, the strain at any state of loading of the beam, depends on the overall deflection of the member. The presence of deviator, may bring the results closer to the bonded tendon condition. Still the non- linear property of the system and the amount of variables associated with the strain level of the reinforcement, loading and deflection pattern, crack widths, residual stress in the members etc. will contribute to the stress level of the external tendon. Limited research had been carried out on the pre-cracked beams and its behavior, in particular to the shear strengthening. The strengthening with clamps in vertical direction for the shear enhancement is analysed in depth by Teng et al.(1996)[25], and is found to be effective. But in practical circumstances, the vertical clamps will not be possible in bridge structures which are operational. So a strengthening mechanism with horizontal or draped external tendon may be more practical. Research by Qi et al.(2015)[17], covers such an aspect, where the effect of draped cable in shear strengthening is studied. Further study on shear strengthening of cracked beams, such as assessing the residual strength of the beam based on the crack width, and assessing the external prestressing requirement would help the industry to implement the repairs in a scientific manner.

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