Numerical Analysis of Strengthening Steel Frames using Post Tensioned Cables

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Abstract - *Strengthening and repairing structures are common procedures that may be considered if the service loads on the structures are increased or the structure exceeds its lifetime. Strengthening and repairing can be applied for both steel and concrete structure. The present study aims at effect of post tensioned cables on strengthening steel frames against earthquake load and improving their load carrying capacity, giving more resistance against the external load (dead plus live or wind load) . Different types of frames are analyzed: simple frame, multi storey frame. The analysis and the results are obtained using ABAQUS finite element (FE) program. The result shows that using post tensioned cables load capacity of steel frame increases and also it enhances the seismic performance.*

***Key Words*: Steel frames, Post tensioning, Cables, Strengthening, Techniques**

1. INTRODUCTION

Sustainable structural solutions are needed more than ever in the construction industry to decrease the carbon-footprint of the built environment. Prestressing techniques are often employed in structural engineering to offer such solutions by enhancing the load-carrying capacity and serviceability performance of structural members and systems. Although prestressing is typically employed in concrete structures, its application in steel structures can also offer benefits. The underlying principle in both cases is essentially the same, where the application of prestress results in the partial or even full cancellation of the stresses that arise at specific regions within the members under loading. However, while in the case of concrete structures the aim is to impose compressive stresses on parts of the cross-section to overcome the intrinsically weak tensile performance and thus prevent cracking, in the prestressed steel frame, the purpose is to enhance the performance of the members by reducing the tensile stress in the bottom flange while increasing the compressive stress in the upper flange. The added compressive stress results in decrease of tensile area and therefore increase the overall capacity of the beam. Previous research studies on prestressed steel structures focused on the application of prestress to hot-rolled steel elements, including bare steel beams, composite beams, steel trusses, tubular members, stayed columns and steel arches; considerable enhancements in load-carrying capacities and reductions in deflections of these members and systems have been reported.

Many steel frames are rendered structurally inadequate with aging of the structure and the increase of loads .Replacement of these structures is costly. Therefore, different structural repairing techniques and strengthening mechanism have been used. Among these repairing and upgrading methods, bolting or welding of steel plates to existing steel beams is one of the most widely used techniques. However there are issues related to this method. For example, the added plates increase the self-weight of the structure. In addition, the welding or bolting process may introduce new stress concentrations in the repaired region, causing a reduction of structural fatigue life .Another strengthening method involves applying carbon-fibre reinforced polymer (CFRP), adding plates or sheets bonded to the web or soffit of steel beams. Benefits are light weight, good durability and ease of handling of FRP materials and this method appeared to be efficient in increasing the load carrying capacity of the existing beams .In addition to these methods, external prestressed tendons have been used to strengthen existing composite steel–concrete beam structures. This technique involves welding end anchorages and using conventional high-strength post-tensioning cables. Results proved that the initial force in the tendon and its eccentricity significantly affect the strength and stiffness of tested beams .Furthermore, this type of strengthening leads to a 25% increase in load carrying capacity in some cases . As an alternative to the above mentioned methods, applying prestressing in a localised region within a steel beam for strengthening existing steel bridges and repairing severely damaged steel I-beams .This method increases the stiffness and the load carrying capacity of the steel structural member through adding reinforcing steel bars to a segment of the beam.

Post tensioning is one of the most effective methods for strengthening an existing structure to overcome the increase in service load without replacement of parts of the structure. Many researchers studied the effect of post tensioning on strengthening steel beams, especially in bridges.

Post-tensioning can be applied to an existing bridge to meet a variety of objectives. Post-tensioning can relieve tension over stresses with respect to service load and fatigue-allowable stresses. These over stresses may be axial tension in truss members or tension associated with flexure, shear, or torsion in bridge stringers, beams, or girders. Post-tensioning also can reduce or reverse undesirable displacements. These displacements may be local, as in the case of cracking, or global, as in the case of excessive bridge deflections. Although post-tensioning is generally not as effective with respect to ultimate strength as with respect to service-load-allowable stresses, it can be used to add ultimate strength to an existing bridge. It is possible to use post-tensioning to change the basic behavior of a bridge from a series of simple spans to continuous spans. Most often post-tensioning has been applied with the objective of controlling longitudinal tension stresses in bridge members under service-loading conditions

Since the 19th century, timber structures have been strengthened by means of king post and queen post-tendon arrangements. The king post and queen post are forms of strengthening by post-tensioning that are still used today, but since the 1950s, post-tensioning has been applied as a strengthening method in many more configurations to almost all common bridge types. The impetus for the recent surge in post-tensioning strengthening is undoubtedly due to its successful history of more than 30 years and the current need for strengthening of bridges in many countries.

1.1 Applicability and Advantage

Post-tensioning has many capabilities: to relieve tension, shear, bending, and torsion-overstress conditions; to reverse un-desirable displacements; to add ultimate strength; to change simple span to continuous span behavior. In addition, post tensioning has some very practical advantages. Traffic interruption is minimal; in some cases, post-tensioning can be applied to a bridge with no traffic interruption. Few site preparations, such as scaffolding, are required. Tendons and anchorages can be prefabricated. Post-tensioning is an efficient use of high strength steel. If tendons are removed at some future date, the bridge will generally be in no worse condition than before strengthening.

1.2 LIMITATIONS AND DISADVANTAGES

When post-tensioning is used as a strengthening method, it increases the allowable stress range by the magnitude of the applied post-tensioning stress. If maximum advantage is taken of the enlarged allowable-stress range, the factor of safety against ultimate load will be reduced. The ultimate load capacity thus will not increase at the same rate as the allowable-stress capacity. For short-term strengthening applications, the reduced factor of safety should not be a limitation, especially in view of the recent trend toward smaller factors of safety in design standards. For long-term strengthening applications, however, the reduced factor of safety may be a limitation. At anchorages and brackets where tendons are attached to the bridge structure, there are high local stresses that require consideration. Any cracks initiated by holes or expansion anchors in the structure will spread with live-load dynamic cycling. Because post-tensioning of an existing bridge affects the entire bridge (beyond the members which are post-tensioned), consideration must be given to the distribution of the induced forces and moments within the structure. If all parallel members are not post-tensioned, if all parallel members are not post-tensioned equally, or if all parallel members do not have the same stiffness, induced forces and moments will be distributed in some manner different from what is assumed in a simple analysis. Post-tensioning does require relatively accurate fabrication and construction and relatively careful monitoring of forces locked into the tendons. Either too much or too little tendon force can cause overstress in the members of the bridge to be strengthened. Tendons, anchorages, and brackets require corrosion protection

1.3 Objectives

- Easy and cost effective method for improving load carrying capacity of steel frames.
- Increase the life span of steel structures through post tension cables.
- Obtain the percentage of improvement in load carrying capacity of post tensioned frames
- To enhance the seismic performance by post tensioned cables.

1.4 Scope

Advanced study on the load bearing capacity of multi storey structures through post tension cables on positive moment region by numerical analysis.

1.5 Methodology

The main objective of this study is strengthening of steel frames using post tensioned cable. For this study ABAQUS is selected .step by step procedure is as follows

1. Literature Review

2. Validation

3. Numerical modeling of steel structures in ABAQUS

4. Numerical Analysis of post tensioned steel structures

5. Comparisons between structures

2. LITERATURE REVIEW

Klaiber et al. (1990) studied the effect of post tensioning on strengthening an existing continuous-span steel-beam with concrete deck bridge. The purpose of his study is to examine the potential for strengthening continuous composite bridges by post-tensioning. Testing of a one-third scale bridge model and finite element analysis are used to determine the effects of various straight-tendon post tensioning schemes. Because of both longitudinal and transverse distribution, the effects of post tensioning are complex. When asymmetrical post tensioning arrangements are applied to the bridge, the resulting stresses add to the dead load stresses in some regions of the model bridge. Symmetrical post tensioning of negative moment regions results in smaller stress reductions than symmetrical post tensioning of positive moment regions. Symmetrical post tensioning of positive moment regions has significant beneficial effects in both negative and positive moment regions. Vertical loads applied to the post tensioned model bridge either increase or decrease tendon forces, depending on the positions of the loads and tendons. Testing and analysis indicate that symmetrical post tensioning could improve service load stresses in continuous composite bridges.

Ayyub et al. (1990) studied the pre-stressing of a composite girder subjected to a positive moment. According to the 1986 U.S. Federal Highway Administration statistics, there are 575,607 bridges on the highway system. About half of these bridges are structurally deficient and/or functionally obsolete. To strengthen the structurally deficient bridges without replacing the girders, external prestressing techniques can be used. His study mainly focused on the behavior of prestressed, composite steel-concrete beams under positive bending moment is examined, and the benefits of different types of prestressing are compared. These specimens were tested to study various aspects of prestressed composite girders, including tendon type and profile. Two methods of analysis are discussed, i.e., the transformed area method and the strain compatibility method. The test results show that prestressing a composite girder increases the range of elastic behavior, reduces deflections, increases ultimate strength, and adds to the redundancy by providing multiple stress paths. Based on the experimental results, a comparison was made between three tendon types and profiles. It was concluded that strands are more effective than bars for the tendon type, and a straight tendon profile is more effective than a draped profile with regard to stiffness.

Ayyub et al. (1992a, 1992b) presented an experimental and analytical study for prestressing composite girder subjected to negative moment .The deflections, forces in the prestressing tendons, and strains in the steel beam and concrete slab of composite girders were computed throughout the entire loading range up to failure. Equations are provided for the calculation of the yield and ultimate load capacities of the girders. The developed analytical models were based on the incremental deformation method. The results of the analytical study were compared with test results of several girders. Reasonably good correlations between analytical and experimental results were obtained. Also, the results showed that a substantial increase in the yield and an increase in the ultimate load capacities can be achieved by adding prestressing tendons to the composite girders and prestressing them. It was determined that the most effective construction sequence for prestressed composite girders in negative moment regions is to post tension the composite girders with tendons in the concrete slabs.

Phares et al. (2003) presented a research on strengthening of steel girder bridges using post tensioned rods of carbon fiber reinforced polymers (CFRP). This paper documents two projects funded through the Federal Highway Administration's Innovative Bridge Research and Construction (IBRC) program. The IBRC program was developed to assist bridge owners in applying emerging technologies in bridge engineering. In these projects, the Iowa Department of Transportation employed techniques for strengthening steel girder bridges using carbon fiber reinforced polymers (CFRP). Two bridges were strengthened using CFRP composite materials in an effort to improve the live load carrying capacity of the bridges. In one case, a bridge was strengthened using CFRP post-tensioning rods in the positive moment regions. In the other case, a bridge was strengthened by installing CFRP plates to the bottom flange of girders in the positive moment regions. It was concluded that the significant effect of using post tensioned CFRP in increasing the load capacity of the bridge.

Nazir (2003) shows that using post tensioned cable for a pre-stressed arch steel bridge has a great effect in reducing stresses on the arch girder. New bridge system Called the prestressed steel arch bridge', its main load bearing members are steel arch ribs that are prestressed with high tensile rock anchors embedded in the banks. The prestressing aims to achieve material economy by relieving the arch rib bending moments induced under self-weight and non-uniform load. The principle design criteria are design of arch rib as tensile arch under prestressing load during self-weight condition and as a conventional arch bridge under live load and temperature variation

Han and Park (2005) studied the elastic behavior of post tensioned steel trusses with straight and draped tendon profiles. The effect of different parameters on the working load and the deflection of truss were studied. These parameters were: tendon profile, truss type, pre-stressing force and tendon eccentricity. It was concluded that post tensioning enlarges the elastic range, increases the redundancy and reduces the deflection and member stresses. As a result, the load carrying capacity of the truss was increased. Nowadays, there are a lot of applications of post tensioned steel trusses for long span roofs especially in stadiums such as Telstra Stadium in Australia.

Mahmoud et al study the effect of post tensioned cables on strengthening steel frames and improving their load carrying capacity, giving more resistance against the external load (dead plus live or wind load). Different types of frames are analyzed: simple frame, double bayrame and double story frame. The analysis and the results are obtained using ANSYS finite element (FE) program. Different techniques were used to apply post tensioning to steel frame. Comparisons are made between these techniques to determine which technique is better in strengthening each type of frame. The results show that using post tensioned cables increases significantly the load capacity of the steel frame.

2.1 Observations from Literature Review

From the literature, it can be concluded that using post tensioned cables is one of the most effective ways in strengthening different types of buildings and structures. All researches that have been carried out before to strengthen steel frame were concentrating in strengthening steel frame corner connection against earthquake load and decreasing their lateral drifts, there is shortage in the researches that seismic behavior of steel frames Strengthened using post tensioned cables. Hence here an attempt to study the seismic behavior of steel frames strengthened by post tensioned cable.

3. STRUCTURAL MODELING

In this study the finite element modeling of the steel frame is done using ABAQUS software. Modeling and analysis of multi storey steel frame with and without post tensioning and analyse the increasing percentage of load capacity through numerical analysis methodology.

3.1 Validation of Model

A numerical example from the literature (Mahmoud et al.2014) has been taken for developing the finite element model of the steel frame in ABAQUS. The frame was assumed to have a span of 30m and height of 10m .The frame's beam is horizontal carbon steel of grade 37(ECP 205(2008)) with yield stress of 250 MPa and youngs modulus of 210 GPa.Own weight of steel is taken as 0.35kN/m2 The most effective technique validate and analysed among prescribed techniques in journal.

The model of the steel frame subjected to the loading is shown in fig-1. Geometrical properties of the steel frame considered is shown in the table 1 & 2.

Table -1: beam cross section

Height of web (h_w)	550 mm
Web thickness (t_w)	12 mm
Flange width (b_f)	210 mm
Flange thickness (t_f)	16 mm

Table -2: column cross section

Height of web (h_w)	600 mm
Web thickness (t_w)	16 mm
Flange width (b_f)	210 mm
Flange thickness (t_f)	24 mm

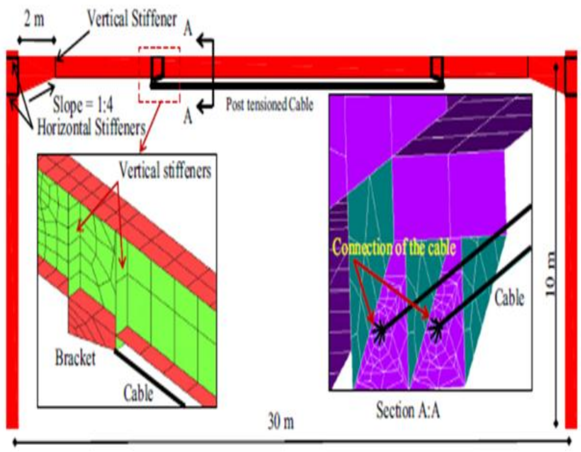

Fig -1: Frame layout

3.2 Analysis

The post tension force was increased gradually till failure occurs in the frame section and obtain various stress and plot XY graph of Post tensioned load v/s percentage of increasing load carrying capacity. The cables that are used in the analysis are of 20mm diameter with ultimate strength of 1960 MPa.Validated model of with and without post tensioned simple frame as shown in fig 2.

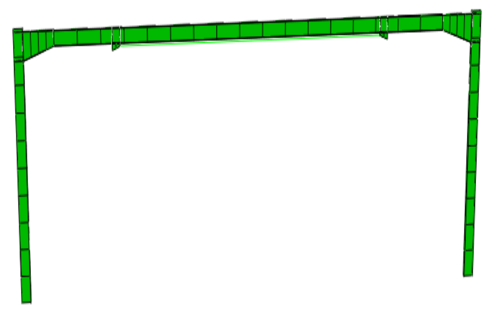

Fig -2: Validated model of post tensioned simple frame

3.3 Result and Discussion

Analyse the stress values obtained against various load from ABAQUS and evaluate the increase in percentage of load capacity of post tensioned simple frame through numerical Analysis. The final result of 29.3% increment in load capacity of post tensioned frame than normal frame of same cross section. The result of increment in load capacity of the FE model are good in agreement with journal. The stress variation of simple frame as shown in fig 3, Analysis details are given in chart 1.

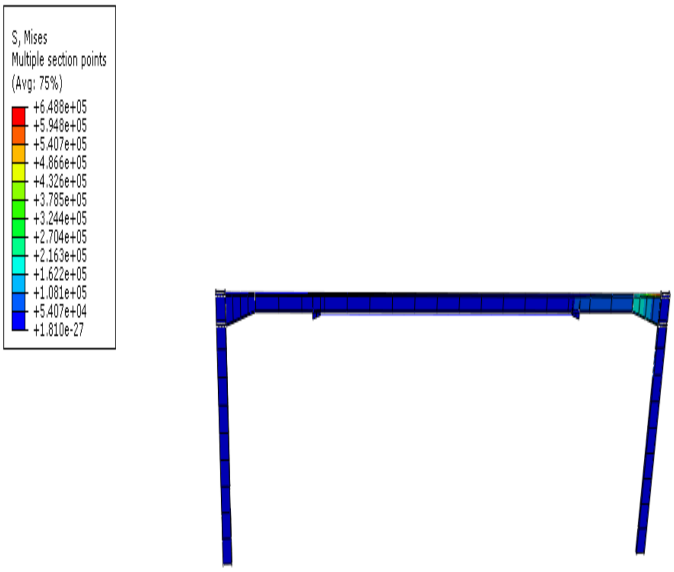

Fig -3: Post tensioned simple frame under stress

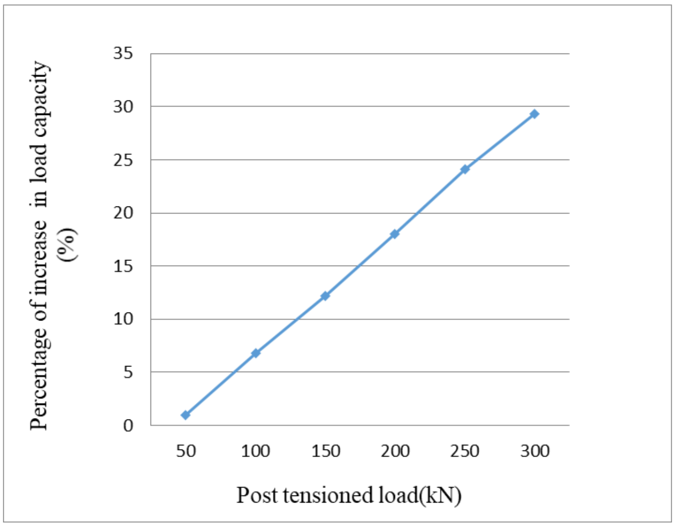

Chart -1: Relation between post tension force and the percentage of increase in the frame load capacity

RESULT : 29.3% increase in load capacity of simple frame.

4. MODELLING AND ANALYSIS OF MULTI STOREY FRAME

This section analyses strengthening of multi storey frame using post tensioned cables with support of ABAQUS simulation. The frame consist of three stories each has 5m height,15 m span and 6 m spacing and the length of the bracket is 500mm two stiffeners are used at the ends of the brackets .The thickness of the bracket plate and the stiffeners are 40 mm ,shell element is used to model the bracket. The cables that are used in the analysis are of 32mm diameter with ultimate strength of 1960 MPa. The cables are attached in positive moment region of the frame.

4.1 Analysis

In the analysis carbon steel of grade 37 and the steel material has a yielding stress of 240 MPa and youngs modulus of 210 GPa. The frame has fixed end bearings. The cables are used in the positive moment region of the beam, two post tensioned cables are used in each beam and column. The post tension force was increased gradually till failure occurs in the frame section and obtain various stress and plot XY graph of Post tensioned load v/s percentage of increasing load carrying capacity. Validated model of with post tensioned multi storey frame as shown in fig -4.

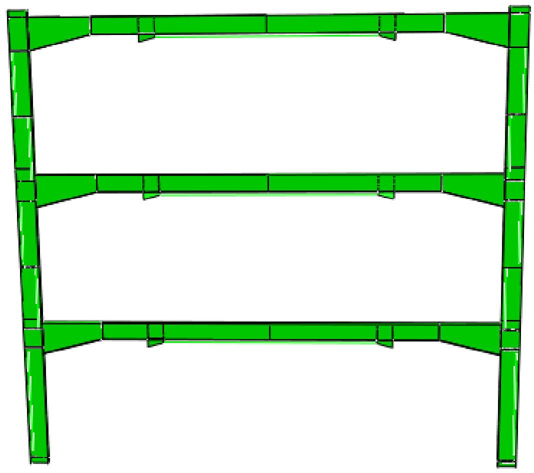

Fig -4: Validated model of post tensioned multi storey frame

4.2 Result and Discussion

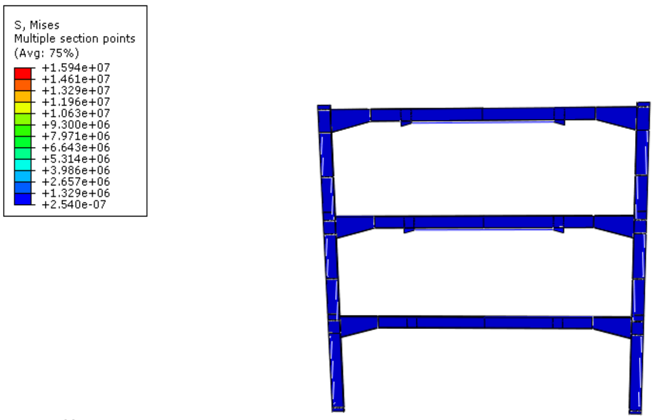

Fig -5: Post tensioned multi frame under stress

Analyse the stress values obtained against various load from ABAQUS and evaluate the increase in percentage of load capacity of post tensioned simple frame through numerical Analysis. The final result of 24.84% increment in load capacity of post tensioned frame than normal frame of same cross section. The stress variation of multi storey frame with post tension as shown in fig 5. Analysis details are given in chart 2.

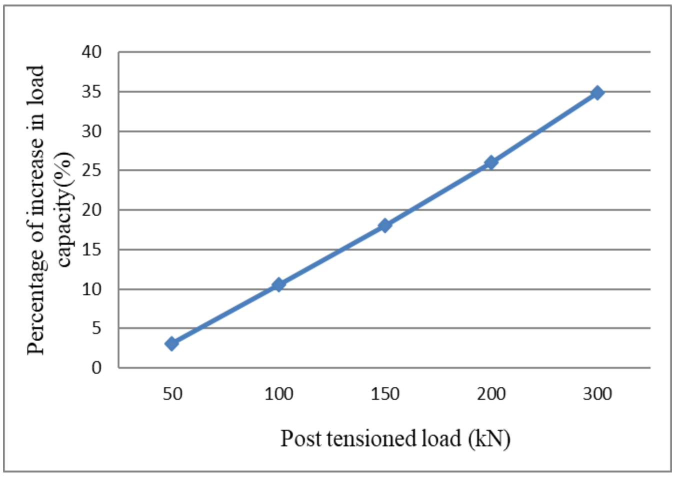

Chart -2: Relation between post tension force and the percentage of increase in the frame load capacity.

RESULT: 34.84% increase in load capacity of multi storey frame.

5. NON LINEAR STATIC ANALYSIS OF MULTI STOREY FRAME

5.1 Storey V/S Displacement

Chart 3 shows the displacement of the three storey frame with and without post tensioning after dynamic time history analysis. Considering the displacement in each stories it can be concluded that the displacement get reduced considerably in all stories after implementation of a post tensioning into the three storied steel frame as compared to the same without post tensioning.

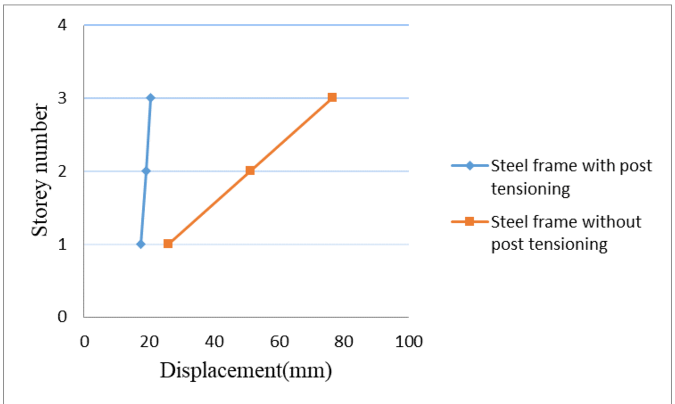

Chart -3: Comparison of displacement of each stories with and without post tensioning.

6. CONCLUSIONS

Non linear analysis using ABAQUS finite element program was adopted to simulate the behavior of the post tensioned frames of simple and multi storey, from the analysis It can be concluded that post tensioned technique is very effective in strengthening different types of frames. Increasing the tension force in the cable will lead to increase the load capacity of the frame till certain level after that failure will be observed at the cable connection due to increasing tension stress in the bracket and stiffener as a result of high tension force in cables. However, this problem can be overcome by improving the cable connection with strengthening steel plate that will delay the failure of the connection . Post tensioned cables can increase the load capacity of the simple frame by around 30% and multi storey frame by around 35%. Finally, strengthening frames using post tensioning cables can be used in repairing structures or as a main system of a newly designed frame.

Using post tensioned cables is also a better technique for enhancing seismic perfomance. It reduces the displacement due to earthquake. The application of this method reduce the material consumption and cost and it can be easily applied in any geographical regions ,in some cases more corrosive protection methods are advisable on the cables.

REFERENCES

[1] D Ayyub, B.M., Sohn, Y.G., Saadatmanesh, H., “Prestressed composite girder under positive moment.” J. Struct. Eng. 116 (11), 2931–295,1990

[2] Ayyub, B.M., Sohn, Y.G., Saadatmanesh, H.,”a. Prestressed composite girder I: experimental study for negative.” J. Struct. Eng. 118 (10), 2743–2762’1992

[3] Ayyub, B.M., Sohn, Y.G., Saadatmanesh, H., “b. Prestressed composite Girder II: analytical study for negative moment.“,J. Struct. Eng. 118 (10), 2763–2782,1992.

[4] Dunker, K.F., Klaiber, F.W., Beck, B.L., Sanders, W.W.,. “Strengthening of existing single-span steel-beam and concrete deck bridges. In: Final Report Part II”. ISU- HR-238, ERI Project 1536, ERIAmes-85231. Engineering Research Institute, Iowa State University, Iowa Department of Transportation Highway Division and the Iowa Highway Research Board.1985.

[5] Ghannam, M., Mahmoud, N.S., Badr, A., Ssalem, F.A., “Strengthening and repairing of an existing steel bridge using post tensioning. “Int. J. Civil Struct. Eng. 5 (2), 91–100,2014.

[6] Han, K.-B., Park, S.-K.”. Parametric study of truss bridges by the post-tensioning method” Canadian. J. Civil Eng. 32 (2), 4020–4429,2005.

[7] Klaiber, F.W., Dunker, K.F., Planck, S.M., Sanders, W.W., "Strengthening of an existing continuous-span, steel-beam, concrete deck bridge by post-tensioning". Final Report, ISU-ERI-Ames- 90210. Engineering Research Institute, Iowa State University, Iowa Department of Transportation Highway Division and the Iowa Highway Research Board, Ames, 1990.

[8] Mahmoud, N.S., Badr, A., Ssalem, F.A., Ghannam, M. "Strengthening steel frames by using post tensioned cable". Life Sci. J. 11 (1), 111–116, 2014.

[9] Phares, B.M., Wipf, T.J., Klaiber, F.W., Abu-Hawash, A., Lee, Y.,."Strengthening of steel girder bridges using FRP". In: Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, Iowa, pp. 1–12,2003.