Stiffening and Strengthening of Deteriorated CellularBeams by Local Post-Tensioning

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Abstract - *Cellular beams have long replaced the conventional I beams with their ability to span greater distances using lesser quantity of steel, their durability and versatility. But their greater depth makes them more prone to corrosion and other deteriorations. Many rehabilitation methods that are currently in use such as installing steel plates and CFRP's are either time consuming or complex. The main purpose of this study is to introduce and investigate the effect of the local post- tensioning method to strengthen the performance of deteriorated cellular beams. Local post-tensioning method uses reinforcing bars and manual jacks to strengthen a beam and improve its load carrying capacity without adding any new material to it. The cellular beams that are prone to deteriorations can be strengthened using this simple and low-cost alternative to the conventional post-tensioning technique. The deteriorations at different parts of the beam are analyzed and the stiffness and strength of the beam are improved by using local post tensioning method and stiffeners. Parameters such as ultimate load, deflection and stiffness are determined and studied. The analysis is performed in ANSYS Workbench software and a more economical and convenient method to rehabilitate a cellular beam is proposed.*

Key Words*: *Cellular beams, Deteriorated beams, Finite element analysis, Local post tensioning, Strengthening and Stiffening.

1. INTRODUCTION

Steel structures play a very vital role in the construction industry. Their discovery dates back to centuries and have undergone many modifications according to the various needs. Cellular beams are one such steel structural member that has always been a key component in construction. They came into existence to overcome the limitations on minimum allowable deflection and to span greater distances. Even after being yesterday's technology, they still continue to be the backbone for most of the major structures you will see. These structures are made by cutting a rolled steel beam using flame along its centre-line and then re-joining the two halves by welding. This increases the overall depth of the beam by 50% for improved structural performance against bending. They are often used to facilitate long spans resulting in flexible, column-free internal spaces, reduced substructure costs and shorter steel erection times.

Currently, the process of fabrication of an original beam into a castellated or cellular beam has become popular as an alternative solution to increase the beam's load carrying capacity, provide greater space for pipe work without affecting the floor height, and improve the aesthetics of the building, without adding steel. In recent decades, engineers and architects sees **cellular beams** in the construction as a perfect combination of aesthetics and function. Even though the strength of the beam increased, some failures that were not present in the original beams were identified and these limited the strength of the cellular beams. Also these steel structures become structurally deficient over time due to their increased depth and severe exposure hence making their rehabilitation more crucial.

This paper studies a method to rehabilitate the cellular beams by a technique known as the local post tensioning method.

The Local Post-Tensioning (LPT) method increases the stiffness and the load carrying capacity of the steel structural member by attaching reinforcing steel bars to a part of thebeam. The steel beam is pre-stressed by elevating thereinforcing bars from the soffit of the beam using a manual screw jack that introduces tensile force in the steel bars. Considering the low cost, easy setup and operation, this method is also being used in concrete beams. The objective of this thesis is to introduce and investigate the local post- tensioning method as a simple and low cost alternative tostiffen and strengthen a cellular I beam and thereby improveits performance.

LPT is a very effective alternative to strengthen existing concrete and timber structures. The results also proved that this innovative technology represents an alternative and a more efficient way to repair and upgrade steel beams when compared to existing methods.

Unlike conventional post-tensioning methods, LPT is applied only to the critical areas. The main idea behind the process in this part of the study is to increase the load carrying capacity of a regular steel I-beam by adding additional reinforcing bars. The reinforcing bars are then tensioned using a manual screw jack.

After the bars were pulled to the required tensile forces calculated using the equation 1.2, a rigid support was placed at the mid-span of each steel bar and the bottom part of the top flange to maintain the stresses developed in the bars in a similar way to that used to restore the load-carrying capacity of severely damaged steel beams. The tensile force developed in the rebar generates a reverse bending moment in the mid-span cross section of the beam that results in the increase of stiffness and load carrying capacity.

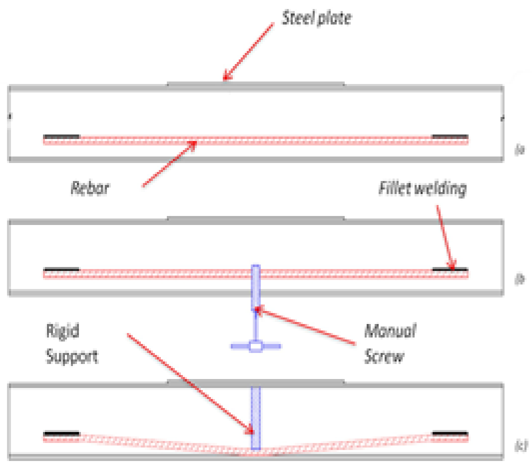

Fig-1:The process of LPT:(a) welding the bars (on both sides),(b) pulling the bars using a manual screw jack,(c) fixing the bars in place using a rigid support. [1]

The jacking distance 'f', the tensile force 'N' within the reinforcement bars that was generated by the pre-stressing process, and the jacking force '*F*', required to generate the tensioning force N, where calculated using Equations 1.1, 1.2 and 1.3 respectively

- $f = l\frac{\sigma}{2E}$ (1.1)
- $N = \sigma A$ (1.2)
- $F = N\sqrt{\frac{8\sigma}{E}}$ (1.3)

2. LITERATURE REVEIW

Phattaraphong Ponsorn et al.,(2020) carried out this study to expose the efficiency conditions, and provide design recommendations to obtain the maximum efficiency based on the AISC design guidelines of cellular beam (CB). Cellular beams have become popular as an alternative solution to providespace for pipe work without compromising the floor height, increase the beam carrying capacity, and provide an aesthetic perspective for the building without adding steel material. Based on these possible shortcomings, this study was carried out to determine the efficiency state of CB utilization and to recommended guidelines for the most efficient design of the beam. This study showed that the beam length is the major variable in determining the efficiency of fabricating as original root beam into a castellated or a cellular beam, as demonstrated previously. However, several other parameters also influenced the efficiency of cellular beam. These parameters include section slenderness ratio, flange slenderness ratio and even the yield strength of steel material.

A. Cyril Thomas et al., (2018) presents the advantages of using carbon fibre reinforced polymers (CFRP) in strengthening of thethin-webbed castellated beam (TCB). These web openings are commonly used for providing the service lines like air ducts, sewage lines or water lines,. The beam was modelled in ABAQUS and to avoid the local buckling at the loading point, stiffeners were provided below the loading point. Parameters such as castellation depth, length of the beam, weld length and strengthening type were studied and was concluded that the CFRP strengthening techniques also increased the overall stiffness of the beam. The performance of castellated beam in flexure was found to be better when its length was high. This is an established advantage of the castellated beams. From the FE study it was observed that the load carrying capacity of the CB section fully depends on its geometrical properties, that is its perforation size and the weld length.

Assaad Taoum et al., (2015) has in his papers performed a series of experiments on the behaviour and effects of the local post tensioning method on conventional I beams.

Studied the upgrading of steel I beam using the local post-tensioning method, which uses reinforcing steel bars and a manual jack to perform post tensioning. The arrangement was kept in place with help of a stiffener. This method of strengthening beam is very simple, cost effective and do not require any skilled labour. The main objective was to increase load carrying capacity of six beams, having three different diameters of reinforcing bars and tensioned internally and externally. A control beam was used to compare the performance of the locally post tensioned beam. The beams were then loaded using the three point loading method and was found that the load carrying capacity of the locally post tensioned beam was increased. The paper also presented a comparison between fire reinforced polymer used in strengthening the beam and it was found that the yield load was doubled in the case of locally tensioned beams.

Damien Holloway et al.,(2015) In his paper investigated the behavior of deteriorated steel beams that are repaired using locally pre- stressed reinforcing steel bars. Regular reinforcing bars are welded to the beam's web at both the ends and are thenpre-tensioned using a manual screw jack to increase the effectiveness of the repair. Six beams with different bar diameters and different levels of pre- stress were repaired and tested under three-points bending. These beams were tested up to failure under fatigue loading until was a crack developed. The main concept of the method proposed in this study is to pullthe crack together by using a manual screw jack to tension two reinforcing bars, one on each side of the web and a rigid support was inserted at the mid span of each steel beam to maintain the stresses in the bars. Three point bending test was done on the locally post tensioned beam and was found that high level pre stressing help the beam recover its rigidity.

Local pre-stress does not require any special equipment or personal training. Application of localized post tensioning onthe reinforcing bars was found to restore 75% of the load-carrying capacity of the damaged beam.

3. MODELLING AND ANALYSIS

3.1 Geometry and Loading

195.82 X 75 X 7.0 X 5.0 mm I-section cellular beam is used.The specimen is of length 1400 mm. 10 holes with an opening diameter of 100 mm. center to center spacing between the holes being 140 mm.

Point load is applied to the beam considering simply supported condition with roller support on both ends. Concentrated load is provided at the center which increases up to the ultimate failure of beam.

Table 1: Material properties

Material	Input parameter	Magnitude
Cellularbeam	Young's modulus	2 X 10^5MPa
	Poison's ratio	0.3
	Yield strength	1.6 MPa

3.2 Modelling of Structure

The steel I section is modelled in ANSYS 19.0 and the material properties of the Steel beam are assigned. The structure is then meshed and loads and boundary conditions are provided. The structure is solved and the deformationand force reactions are studied.

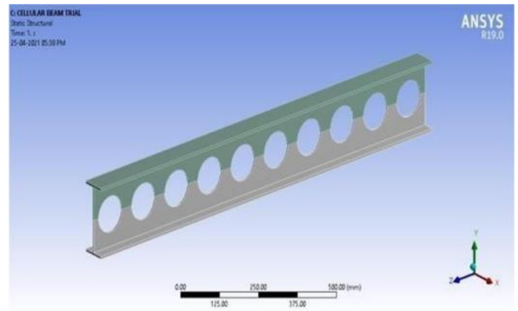

Fig-2: Model of steel cellular beam in ANSYS

In this study coarse meshing is adopted and mesh size varies from 6mm to 20 mm. The element type adopted is SOLID 186 and the mesh shape is hexahedron. The sizing function is adaptive meshing method. Meshing of the model in ANSYS is shown in Figure 3.

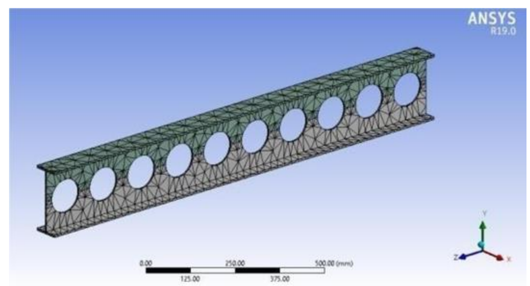

Fig-3: Meshing of the cellular model

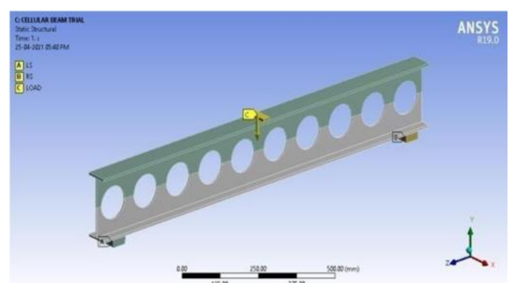

Fig-4: Loading and boundary conditions ofcellular beam

The performance of normal I beam and cellular beam modelled in ANSYS are studied and compared. The corresponding force reaction and moment reaction are analysed and a graph is plotted between the two in order to understand the efficiency of a cellular beam when compared with a normal I beam.

In order to further understand the behaviour of cellular beams when exposed to external environmental conditions and make the best use of them, the beams were subjected to certain deteriorations.

Steel structure besides having huge advantages has got some serious drawbacks which are mostly deteriorations especially due to corrosion when exposed to the atmosphere. Unlike conventional steel beams cellular beams have openings on their web which makes these beams more exposed and hence prone to deteriorations. Corrosion can be related with loss in mass or area of a particular section. In this study the loss of area of steel from the surface is taken into consideration, thus the main effectof corrosion will be thinner structural sections.

In order to study the change in behaviour of beams when corrosion occurs at different parts of the beam, each part like the flange and web are subjected to corrosion. Both the cases are studied for three different stages of corrosion. That is 25%, 50% and 75% and the worst caseamong them is identified.

3.3 Strengthening of cellular beam

After conducting a detailed analysis on the performance of cellular beams subjected to corrosion at different parts of the beam it was concluded that corrosion at the web of the beam hadthe worst effect. This serious deterioration that occurs in a beam due to corrosion can be controlled and prevented to a great extend using certain strengthening measures.

The most important and common rehabilitation measure that canbe taken in this case is to provide stiffeners on the web of the beam. Stiffeners are also known as secondary plates that are attached to a beam's web or flange in order to prevent out of plane deformations or buckling, or in simple terms to stiffen the beam. But stiffeners can only delay the failure by preventing buckling, they cannot actually improve the performance of the beam any further. In order to regain the strength lost by the beam due to corrosion and make it strong enough to withstand the load that comes on it withoutadding or replacing any part of the beam LOCAL POST TENSIONING technique can be used. The worst case of deterioration as identified from the previous analysis was found to result in a decrease of 66% in load. Hence this condition was taken for further analysis to strengthen using the local post tensioning method. After understanding the performance of the locally post tensioned beam, it is compared with the improvement in the performance of beam by using stiffeners alone. And finally the performance of the beam when combining the local post tensioning method and stiffeners are also analysed.

3.4 Modeling of the structure with local post tensioning

The cellular beam with deteriorations at the web was modified by placing reinforcing bars at the bottom of the beam as shown in fig 5. Two bars of 12 mm diameter each were connected using bonded connection in ANSYS to a plate at the bottom of the cellular beam. The reinforcing bars were pulled down to attain a jacking distance that would generate the desired tensile stresses in the beam. In order to maintain the stresses developed in the beam as a result of the local post tensioning a stiffener was inserted between the mid-span of each steel bar and the bottom part of the flange.

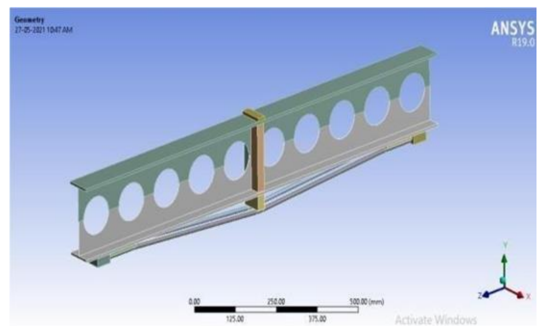

Fig-5: Strengthening with local post tensioning

3.5 Loading and boundary condition

The cellular beam modelled in the ANSYS workbench was loaded in two consecutive steps. First the deteriorated cellular beam was strengthened using the local post tensioning method (fig 6), this was done by providing a jacking force F (Eq. 1.3) that would result in attaining the required tensile stress N in the beam. This tensile stress will in turn generate a reversible bending moment at the mid-span cross section of the cellular beam that will improve its load carrying capacity. The jacking force was calculated and equally divided into the two reinforcing bars.

Following the local post tensioning an axial compressive force was applied from the top at the point C as shown in figure 7. A force that could generate a maximum of 50 mm deflection was provided.

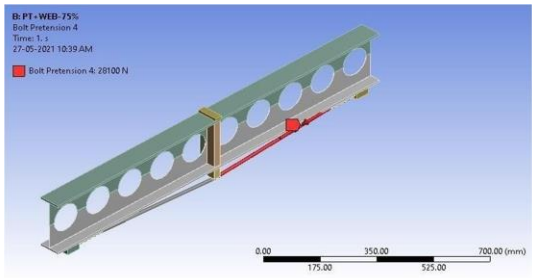

Fig-6: Local post tensioning the cellular beam

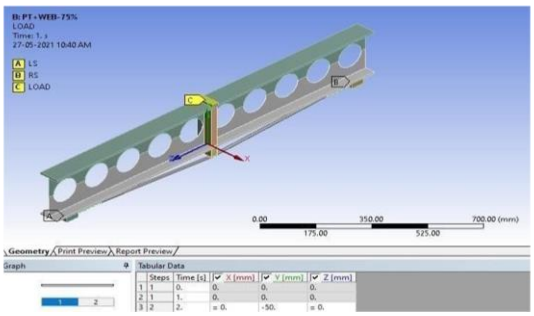

Fig-7: Loading the cellular beam after LPT

3.6 Stiffening the cellular beam

In a cellular beam, stress concentration occurs near the holes on the web and the shear carrying capacity of the beam is reduced. The stress distribution within the member is altered and these openings decrease the stiffness of the beams resulting in larger deflection. The main focus of the research work is to study the effect of introducing stiffeners along the web of the beam so that deflection is minimized and shear failure is controlled.

Stiffeners were provided in various arrangements in order to obtain the maximum efficiency. Both ring stiffeners and vertical stiffeners were used to strengthen the beam. Ring stiffeners were provided around the holes of the cellular beam to take care of the shear concentrations developed here and the vertical stiffeners were provided between each holes of the cellular beam. The stiffeners were each of thickness 5 mm and the ring stiffeners were of 10 mm width and the vertical stiffeners with the width of the flange ie.75mm.

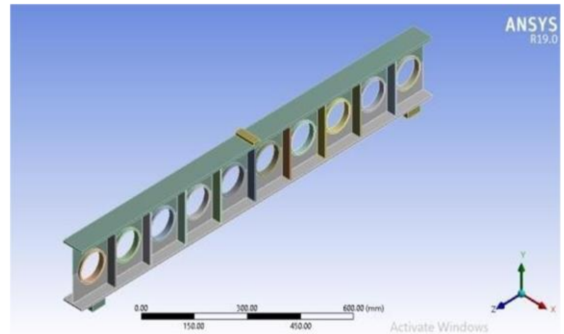

Fig-8: Strengthening with vertical stiffeners and ring stiffeners

3.7 Combining the local post tensioning and stiffeners

The Local post tensioning method and stiffeners are combined together to analyse the effect they have on a deteriorated cellularbeam. The stiffener arrangements adopted in the previous section is considered here with local post tensioning applied in all the cases.

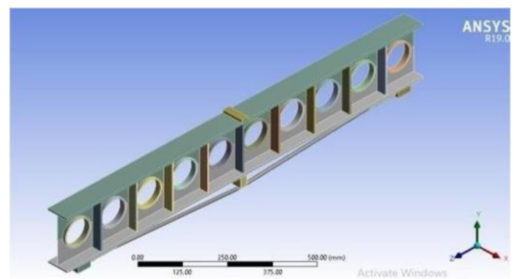

Fig-9: Strengthening with LPT, ring stiffeners and vertical stiffeners

4. RESULT AND DISCUSSION

The data obtained from the analysis are as follows:

Table 2: Percentage increase in strength due to stiffeners

	DEFLECTION (mm)	**LOAD (kN)**	**% of increase in strength**
CELLULAR BEAM	35.10	152.01	66.99
COR @ WEB75%	35.09	50.17	1.00
POST TENSIONED	28.31	74.17	47.84
STIFFENED(RS)	55.502	81.73	62.91

STIFFENED(VS)	175.26	87.72	74.85
STIFFENED(ALTERNATE RS+VS)	105.9	110.13	119.53
STIFFENED(RS+ALTERANTE VS)	30.258	88.53	76.47
STIFFENED(RS+VS)	85.03	118.87	136.95

Table 3: Percentage increase in strength due to stiffeners and local post tensioning

	DEFLECTION (mm)	LOAD (kN)	% of increase in strength
CELLULAR BEAM	35.10	152.01	66.99
COR @ WEB75%	35.09	50.17	1.00
POST TENSIONED	28.31	74.17	47.84
PT+STIFFENED(RS)	6.8901	95.11	89.58
PT+STIFFENED(VS)	9.2132	103.88	107.07
PT+STIFFENED (ALTERNATE RS+VS)	10.119	136.16	171.41
PT+STIFFENED (RS+ALTERANTE VS)	7.7026	128.17	155.49
PT+STIFFENED (RS+VS)	5.92	145.03	189.09

The local post tensioning method was found to attain half of the strength that was lost by the beam due to corrosion. Stiffeners also showed comparatively similar performance, hence combining both these methods we could achieve a beam that had a better load carrying capacity.

Also it was seen that on combining both the strengthening techniques the deflection of the beam was reduced by a great extend. The improvement in the load carrying capacity and the low deflection values can be accounted for the reversible bending moment that was generated at the mid-span cross section of the cellular beam by the local post tensioning and the ability of the stiffeners to resist buckling.

5. CONCLUSION

The following conclusions were made from the study

1. Cellular beam was found to perform better than the conventional I beam with reduced deflection, greater moment of inertia and high strength to weight ratio. The beam was more economic with the ability to span greater distance. Cellular beam had almost 11.57% greater moment capacity than the conventional I beam

2. Deteriorations affect cellular beam severely, the presence of openings and increased depth of the beam resulted in the corrosion of different parts of the beam. From a detailed analysis it was found that corrosion at the web results in worst performance of beam with 67% reduction in load carrying capacity.

3. Proper strengthening measures need to be adopted to make the best out of cellular beams.

   Considering the drawbacks of the existing conventional techniques the Local post tensioning method was used to strengthen the deteriorated beam. The performance of the beam was found to improve and an increase of 47.84 % in strength was observed. The local post tensioning method was seen to be very used friendly and economical. The reverse bending moment generated due to local post tensioning was very effective in improving the load carrying capacity of the beam.

4. In order to compare the effect of using stiffeners to the localized post tensioning the cellular beam was strengthened using stiffeners and the arrangements of the stiffeners were varied and analyzed. The results showed that using ring and vertical stiffeners increase the strength by almost 60-70% but the stiffeners resulted in large deflections of about 144 mm at the ultimate load.

5. The local post tensioning and the stiffeners were combined to study the extend by which the deteriorated beam can be strengthened. It was found that on combining both the strengthening techniques the load carrying capacity of the beam was increased to about 145.03 kN from 50.15 kN of the cellular beam, which is almost near to the load carrying capacity of the original cellular beam that has not undergone any corrosion ie. 152.01 kN. Combination of both the strengthening techniques resulted in a great increase in the strength and was found to be performing almost similarly to the original cellular beam.

It can be hence drawn as a conclusion that local post tensioning alone is a good strengthening technique that can be adopted, which when combined with the stiffeners give a performance similar to that of the initial cellular beam.

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