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Effect of post tensioning on strengthening different types of steel frames

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KEYWORDS

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Abstract The aim of this paper is to 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 bay frame 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.

1. Introduction

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 as presented by Soudki et al. (2012). 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. The aim of this paper is to study the effect of post tensioning in strengthening different types of steel frames and find the suitable way to apply post tensioning in each type. Many researchers studied the effect of post tensioning on strengthening different types of structures.

Many researchers studied the effect of post tensioning on strengthening steel beams, especially in bridges. Dunker et al. (1985) presented a research concerning strengthening of existing single-span steel-beam with concrete deck bridges. Klaiber et al. (1990) studied the effect of post tensioning on strengthening an existing continuous-span steel-beam with concrete deck bridge. It was concluded that post tensioning is a viable, economical strengthening technique. Ayyub et al. (1990) studied the pre-stressing of a composite girder subjected to a positive moment. It was concluded that using strands is preferable than using bars in post-tensioning. Ayyub et al. (1992a, 1992b) presented an experimental and analytical study for prestressing composite girder subjected to negative moment. The research shows that using post tensioning decreases the crack in the negative moment region and reduces the required steel.

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Phares et al. (2003) presented a research on strengthening of steel girder bridges using post tensioned rods of carbon fiber reinforced polymers (CFRP). The research shows 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.

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 Manley (2006).

As the effect of post tensioning cables in strengthening different types of structure becomes obvious, many researchers (Petty (1999), Ricles et al. (2006), Wang and Filiatrault (2008) and Rojas et al. (2008)) used post tensioning cable in earthquake-resistant structural steel moment resisting frame (MRF) system, which are known as self-centering moment-resisting frame (SC-MRF) structural system. This type of connection uses high strength post tensioned cables to pre-compress the beams to the columns and to close the gaps that were developed under earthquake loading, returning the frame to its initial position (Lin et al., 2013). Vasdravellis et al. (2013) proposed a new self-centering beam-to-column connection. The connection used post tensioned high strength steel bars to provide self-centering capability and designed energy-dissipation (ED) elements that consist of steel cylindrical pins with an hourglass shape. The connection performance was experimentally validated under quasi-static cyclic loading. The experimental results show that the proposed connection eliminates residual drifts and beam damage for drifts lower than or equal to 6%. A simplified analytical method was proposed, which predict accurately the connection's behavior. From the experimental results, it was found that the proposed ED elements can be easily replaced without welding or bolting, which means that the proposed connection can be repaired without disturbance to the uses or occupation of the building.

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. It was also observed that post tensioned cables were used in self-centering moment-resisting frame (SC-MRF) to resist earthquake load. In the SC-MRF usually cables are concentric with the horizontal beam of the frame. However, using post tensioned cable with an eccentricity from the beam's or column's center line to resist the working load (dead and live load) was not studied before. 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 study improving the load capacity of the frames' beams and columns using post tensioned cables. The aim of this paper is to introduce new techniques that can be used in strengthening different types of steel frame. These techniques aim to increase the load capacity of steel frames' beams and columns using eccentric post tension cables. This paper is considered as a continuation of the work that has been done by Mahmoud et al. (2014) which shows that post tensioning can increase the load capacity of single bay frame by 30%. As mentioned in this paper, different types of steel frames were strengthened using post tensioned cables. The types of these frames are: single horizontal roof, double bay and two story frame. The geometrical and material properties of these frames were selected as they represent typical properties of a previously designed factory buildings in Egypt.

2. Finite element (FE) Model

Nonlinear analysis using ANSYS 10.0 (2005) finite element program was adopted to simulate the behavior of the post tensioned frames. The analysis was done according to two loading cases, one loading case include the acting loads (dead plus live or wind loads) without post tensioned force. The other case includes the acting load plus the post tensioned load. The post tension force in the cable was increased gradually till failure occurs in the frame section or in the bracket where the cables are attached. The failure was determined when the stress in the steel section reached its yielding strength or if failure occurred due to local or global buckling in compression elements.

The FE model used in this study was verified against field measurement of an existing bride in Iowa, USA, which was strengthened using post tensioning technique as presented in Klaiber et al. (1993). The details, description of the bride and the verified FE model results are presented by Ghannam et al. (2014). Shell element (63) is used to model the columns, beam and the stiffeners. Beam element (4) is used to model bolts at the beam column joints. Each bolt is modeled using 8 beam element arranged at the circumference of the bolt diameter as shown in Fig. 1. This arrangement has been considered to avoid concentration of the stress that would occur if the bolt is model through only one beam element. It should be noted that the total area of the 8 beam element used to simulate the bolt is equal to the actual bolt area.

Beam element (4) is used to represent the cable in the finite element model. It should be noted that only axial stiffness is considered while the flexural stiffness is ignored when modeling the cable. Pretension element (179) is used to simulate the post tensioned load in the cable. Similar to the bolt simulation, the connection between the cable and the bracket is represented by eight Beam element (4) connected to 8 nodes in the bracket to avoid concentration of the stresses that would occur if the cable connection with bracket is simulated through one point, as a result of the high tensile force in the cable.

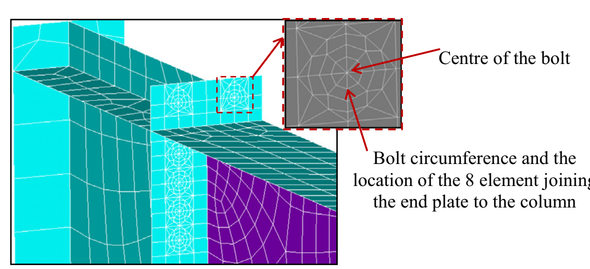

Figure 1 Details of the bolted connection simulation.

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The contact between end plate and the column's flange is achieved using contact element (52), which can carry axial compression and shear force between the surfaces of contact. Fine mesh is used at the location of concentration of the stresses and coarse mesh is used at the location where there is small variation in the stress along the length of the element. The largest aspect ratio used is 2. It should be noted that the element types and meshing size of the frame, cables and its connections are the same in all strengthening techniques that are used for different types of frames.

3. Strengthening of simple frame

3.1. Frame detail

This section describes different post tensioning techniques used to strengthen single bay simple frame. The frame was assumed to have a span of 30 m and height of 10 m. The frame was a part of workshop consisting of multiple frames with spacing of 6 m. The frame's beam is horizontal; the frame material is a carbon steel of grade 37 as per the Egyptian code (ECP 205 (2008)). The steel material has a yielding stress of 240 MPa and young's modulus of 210 GPa. The frame has fixed end bearings.

The own weight of the steel frame is taken as 0.35 KN/m^2, the roof covering material is taken as corrugated steel sheets and its weight is assumed to be 0.15 KN/m^2 .The live load is taken according to the Egyptian code of loading (ECP 201 (2008)) for un-accessible roof, which is equivalent to 0.6 KN/m^2. The total applied load distributed on the frame is 6.6 KN/m'.

The beam's cross section is taken as follows: height of web (h_w) is 550 mm, web thickness (t_w) is 12 mm, width of the flange (b_f) is 210 mm, and flange thickness (t_f) is 16 mm. At the connection between the beam and the column, the beam section is tapered with a slope of 1:4 for 2 m length, as indicated in Fig. 2.

The column's cross section is taken as follows: h_w is 600 mm, t_w is 16 mm, b_f is 210 mm and t_f is 24 mm. The thickness of vertical and horizontal stiffener is taken as 16 mm. The locations of the stiffeners are indicated in Fig. 2. The connections between columns and beam are bolted using M24 grade 10.9. The bolts that were used are ordinary non pretension bolts.

Three post tensioning techniques using post tensioned cable were used to strengthen the frame. The details for each technique are indicated in the following sub sections. It should be noted that the cables that are used in the analysis are of 20 mm diameter (11/4 wire) with ultimate strength of 1960 MPa. In each technique, the post tension force was increased gradually till failure occurs in the frame section or in the bracket where the cables are attached.

3.2. 1st technique

In this technique, the cables are used in the positive moment region of the beam. Two post tensioned cables are used between the two inflection points of the beam's bending moment with a total length of 18 m. The cables are attached to a bracket 120 mm below the lower beam's flange; the length of the bracket is 500 mm. Two stiffeners are used at the ends of the brackets. The thickness of the bracket's plate and the stiffeners are 40 mm. Shell element (63) is used to model the bracket. The connection between the cable and the bracket is indicated in Fig. 2. It should be mentioned that not all techniques in this paper are supplied with indicating figures due to the pages limits.

3.3. 2nd technique

In this technique, two post tensioned cables are used in the positive moment region of the beam. The post tensioned cables that are used in the positive moment region have the same profile and dimension as the 1st technique. Another two post tensioned cables are used in the negative moment region of the beam. The cables are attached from one side to the column interior flange and attached from the other side to the vertical stiffener of the bracket that are holding the cables in the positive moment region. The cables in the negative moment region are attached 40 mm below the upper flange of the beam. The post tensioned cable used in the negative moment region has a length of 6 m.

3.4. 3rd technique

In this technique two cables are attached between the two column's inner flanges and pass through a steel roller of 40 mm diameter welded to the beam's lower flange as indicated in

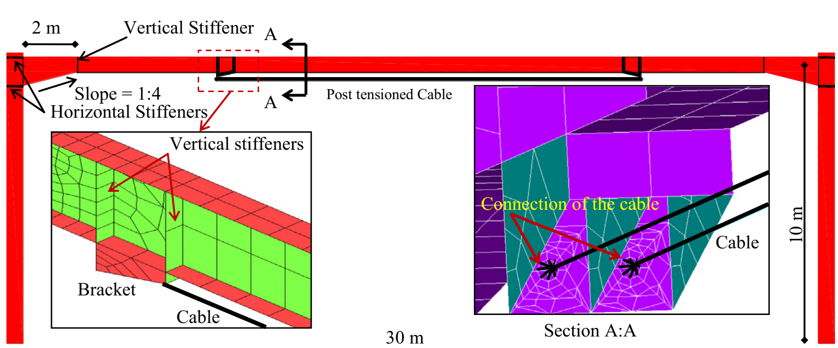

Figure 2 Layout of the 1st technique used in the simple frame.

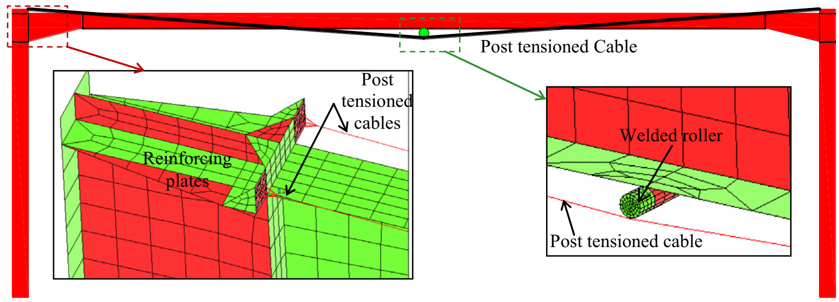

Figure 3 Layout of the 3rd technique used in the simple frame.

Fig. 3. The connection of the cables with the column's flange is stiffened by plates of 40 mm, as indicated in Fig. 3. Contact element (52) is used to simulate the connection between the roller and the cable.

4. Strengthening of double bay frame

4.1. Frame details

In this section the details of double bay frame are introduced. The frame is formed of two spans, each has a length of 25 m. The frame height is 12 m. The main material of the frame is carbon steel of grade 37 as per the Egyptian code (ECP 205 (2008)). The bases of the frame are hinged.

Dead load includes the own weight of the steel frame and a concrete roof of 100 mm thickness. Live load is assumed according to the Egyptian code of loading (ECP 201 (2008)). The total applied uniform load on the beams is 29.1 KN/m'. The layout of the frame is indicated in Fig. 4.

The beams of the frame are horizontal, the beam cross section is as follows; h_w = 800 mm, t_w = 14 mm, b_f = 300 mm and t_f = 26 mm. At the connection between the beams and the outer columns, the beam section is tapered with a slop of 1:8.8 for 2200 mm length. Tapered section is used at the connection between the beams and the inner columns with a slop of 1:4.3 for 2600 mm length.

A tapered section is used for the outer columns, where the top section is: h_w = 800 mm, t_w = 14 mm, b_f = 300 mm and t_f = 26 mm. The section at the bottom is: h_w = 400 mm, t_w = 14 mm, b_f = 300 mm and t_f = 26 mm. The dimension of the interior column is: h_w = 550 mm, t_w = 14 mm b_f = 300 mm and t_f = 26 mm. Stiffeners are used with thickness of 14 mm. The connections between columns and beam are bolted with M24 grade 10.9. It should be noted that the element's types and size of mesh are the same as those used in the simple frame case. The frame was strengthened using post tensioned cables. Two techniques of post tensioned cable are used; these techniques are described in detail in the following sub sections. It should be noted that the cables that are used in the analysis are of 32 mm diameter (11/4 wire) with ultimate strength of 1960 MPa. The applied post tensioned force on the cable is 100 KN.

4.2. 1st technique

Two post tensioned cables are used between the inflection points of the moment of the beam in each bay of the frame as indicated in Fig. 4. The thickness of the bracket supporting the cables is 40 mm to avoid any failure at that location. The cables are placed at 200 mm under the bottom flange of the beam. It should be noted that the element types and meshing size of cables and its connection that was used in strengthening techniques of the simple frame is adopted here.

4.3. 2nd technique

In this technique, two cables are post tensioned in the positive moment regions of the two bays. Another two cables are post tensioned in the negative moment region over the interior column. In this technique, five trials are used to determine the suitable length of the cables located in the positive and the negative moment regions.

4.3.1. Trial 1

In this technique, two cables are post tensioned in the positive moment regions of the two bays. Another two cables are post tensioned in the negative moment region over the interior column. Cables in the negative moment region are connected to the vertical stiffeners of the bracket that are carrying the cables in the positive moment region.

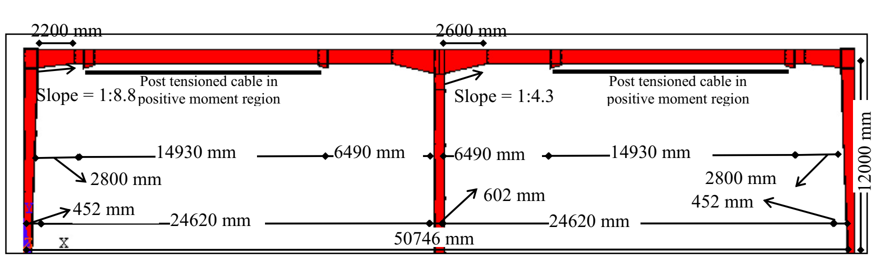

Figure 4 Layout of the 1st technique used in the double bay frame.

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4.3.2. Trial 2

In this trial, the two cables that are used in the negative moment region, are located over the interior column joining between the vertical stiffeners at the end of the tapered beam section of each bay.

4.3.3. Trial 3

In this trial, the cables located in the negative moment region have the same profile as trial 2, while the length of the cable in the positive moment region is reduced to 8930 mm instead of 14,930 mm.

4.3.4. Trial 4

This trail is similar to trial 3. However, the length of the cable in the positive moment region is increased to 10,930 mm instead of 8930 mm.

4.3.5. Trial 5

This trail is similar to trial 3. However, the length of the cable in the positive moment region is increased to 12,930 mm instead of 8930 mm.

5. Strengthening of two story frame

5.1. Frame details

This section studies the strengthening of multi-story frame using post tensioned cables. The frame used for this study consists of two stories each has 5 m height, 15 m span and 6 m spacing. Carbon steel of grade 37 as per the ECP 205 (2008) is used for the main parts of the frame. The bases of the frame are hinged.

The dead load includes the own weight of the steel frame, which is assumed = 0.3 KN/m^2. The floor is covered by a concrete slab of 12 cm thickness. The live load for the 1st story is equal to 3 KN/m^2 and 2 KN/m^2 for the 2nd story according to the ECP 201 (2008). The total uniform load on the frame is 37.8 KN/m' on the 1st story and 31.8 KN/m' on the 2nd story.

The sections of the designed frame are indicated as follows:

For beam: h_w = 600 mm, t_w = 12 mm, b_f = 200 mm and t_f = 20 mm. At the beam column connection the beam has a tapered section with slope 1:4, its length = 1500 mm as shown in Fig. 5. For columns: h_w = 600 mm, t_w = 14 mm, b_f = 200 mm and t_f = 24 mm. The vertical and horizontal stiffeners have a thickness of 10 mm.

The connection between the column and beam is bolted, 3 stiffeners of 20 mm thickness are used at the location of the connection between the beam's upper flange and the plate of the corner connection. The elements types and meshing that are used in the previous two cases of the simple and double bay frames technique are adopted here. Two techniques are used to model the strengthening of the frame using post tensioning cables; these two techniques are discussed in detail in the following two sub sections. It should be noted that the cables that are used in the analysis are of 32 mm diameter (11/4 wire) with ultimate strength of 1960 MPa. The connection between the beam and the column is the same as indicted in the previous two cases of the simple and double bay frame.

5.2. 1st Technique

In this technique, two cables are post tensioned in the positive moment region of the beams. The post tensioned cables are used between the inflection points of the beams. The thickness of the plates forming the bracket which is supporting the cables is 40 mm. This was designed to avoid failure in this location due to the concentration of stress. The cables have an eccentricity of 300 mm below the bottom flange of the beam, the cables' lengths are 6000 mm. Two vertical stiffeners with thickness of 40 mm are joining the top and the bottom flange of the beam at the bracket's ends. Typical details of the bracket are the same as given in Fig. 2.

5.3. 2nd Technique

In this technique, the beams are strengthened using the same profile of the 1st technique. The difference between the 1st and 2nd techniques is that additional cables are post tensioned in the positive moment region (tension stress) of the column. Two trials are used in this technique to specify the best cable profile used in the columns of the frame.

5.3.1. Trial 1

In this trial, the cables that are used in the top of the column of the second story are attached to the horizontal stiffeners which are located opposite to the compression flange of the beam as

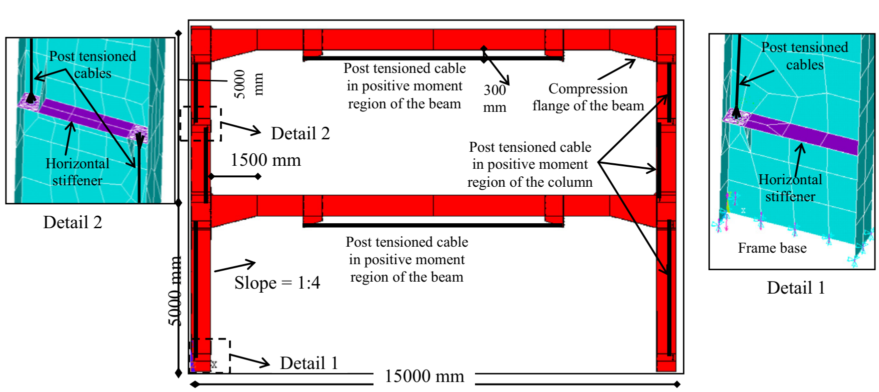

Figure 5 Layout for the trial 1 of the 2nd technique used in the two story frame.

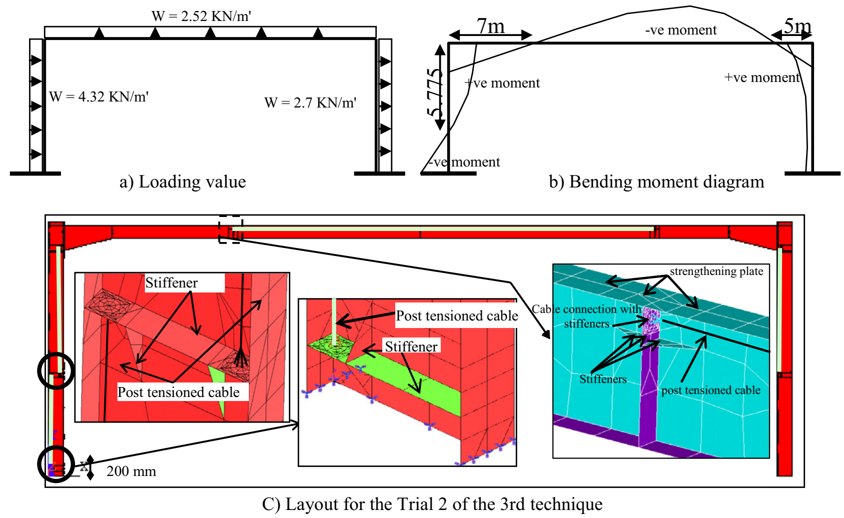

Figure 6 (a) Loading (b) bending moment diagram (c) layout for the Trial 2 of the 3rd technique in case of wind load is governing the design of the steel frame.

indicated in Fig. 5. Fig. 5 shows the details of the cables' connections with the horizontal stiffeners at the mid of the second story and at the base.

5.3.2. Trial 2

This trial has the same cable's profile as of trial 1. However, in this trial, the cables that are used in the top of the column of the second story are attached to the horizontal stiffeners which is located opposite to the tension flange of the beam.

6. Strengthening of wind load acting on single frame

6.1. Frame details

In the previous section different techniques for different king of steel frames were presented. However, it was assumed that the primary loads (dead and live load) are governing the design of these types of frame, which represent the a large part of steel building design in Egypt as wind load is not significant in most of Egypt's provinces.

In other provinces especially Marsa Matruh, wind load may govern steel building design. This section study the strengthening of single steel frame where the wind load is governing the design. The studied frame has the same details as the single frame presented in Section 1. The loading and the bending moment diagram is indicated in Fig. 6. Three techniques were considered in strengthening this type of frame, these techniques are described below.

6.2. 1st Technique

Two post tensioned cables are used between the two inflection points of the frame's beam. The cables are attached to stiffeners fixed at the inflection point of the beam, the cables have an eccentricity of 60 mm under the top flange of the beam, the thickness of the stiffeners is 40 mm. Additional strengthening plate for the flange of thickness equal 24 mm is used at the connection of the stiffener with the upper flange of the beam.

6.3. 2nd Technique

Post tensioned cables are used only in the columns. In this technique, 3 trials are used and they are briefly described below.

6.3.1. Trial 1

The cables are used in the positive moment region of the columns. For the left column two post tensioned cables are used between the inflection point of the column and the bottom stiffener of the beam column connection, the cables have an eccentricity of 60 mm from the inner flange of the column. Vertical stiffener is used at the connection of the cables with the horizontal stiffeners. Strengthening plates of thickness equal 16 mm are used for the column flange at the connection of the stiffener with the inner flange of the column. The same location of the cables, stiffeners and strengthening plate are used for the right column.

6.3.2. Trial 2

This Trial is the same as Trial 1, but in trail 2, the cable is attached between the inflection point of the column and 1 m below the bottom stiffener of the beam column connection.

6.3.3. Trial 3

This Trial is the same as trial 1, but in this trial, the cable is attached between the inflection point of the column and Top stiffener of the bam column connection.

6.4. 3rd Technique

This technique can be considered as a combination of the 1st and the second techniques where the post tension cables are used in both the beam and the columns. Four Trials are used in this technique.

6.4.1. Trial 1

This technique is a combination between 1st technique and Trial 1 of the 2nd technique.

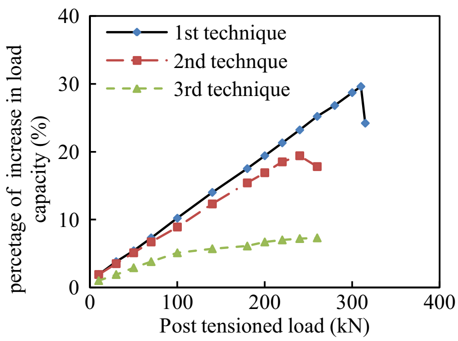

Figure 7 Percentage of increase in the simple frame load capacity using different techniques.

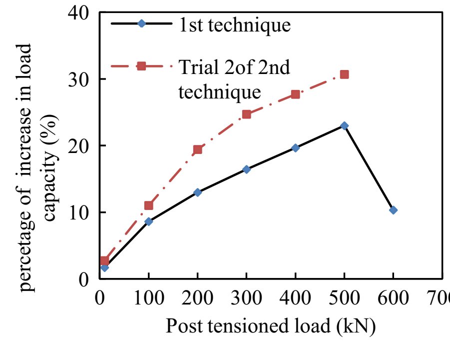

Figure 8 Percentage of increase in double bay frame load capacity using different techniques.

6.4.2. Trial 2

This Trial is the same as the Trial 1 but in this trial, post tension cable is added to the left column between the inflection point and over the base by 200 mm (negative moment region) as indicated in Fig 6.

6.4.3. Trial 3

This trial is the same as the Trial 2 but the post tension cables at the negative moment region of the left column are ended over the base by 1500 mm.

6.4.4. Trial 4

This trial is the same as Trial 2 but the post tension cables at the negative moment region of the left column are ended at the location of the base.

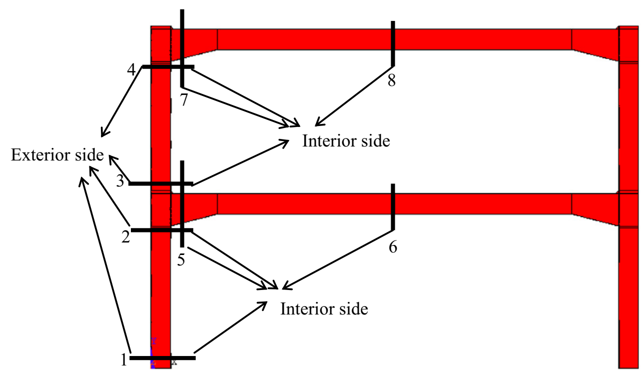

Figure 9 Location of different section used in the comparison between different techniques of the two story frame.

7. Results an discussion

This section provide the results that are obtained for each strengthening technique for different types of frames.

7.1. Simple frame

Fig. 7 shows the relation between post tension force in each cable and the percentage of increase in the frame load capacity. It can be concluded that the 1 st technique is the best technique in strengthening a simple steel frame. 2nd technique reduces stress much on the beam of the frame. However part of the reduced moment on the beam is transferred to the column and thus increase the stress on the column. The 3rd technique gives the lowest reduction of stress compared to the other 2 techniques.

It can be observed from Fig. 7 that in case of 1st and 2nd techniques the percentage of increase in the load capacity began to decrease after a certain level of post tensioning. This occurred due to the failure of the plates connected to the cable. The failure of these plates is a result of increasing the stresses at the location of cables connection as a result of high tension force in the cable. However this problem can be overcome by increasing plate thickness at the location of cable connection.

Table 1 Comparison between different techniques used to strengthen the double bay frame.

Strengthening technique	$\sigma_{N,b}$		$\sigma_{sh,b}$	Δ_b	$\sigma_{N,c,e}$		$\sigma_{N,c,m}$
	Tension (MPa)	Compression (MPa)	(MPa)	(mm)	Tension (MPa)	Compression (MPa)	(MPa)
Frame without post tensioning	146	−191.1	−66.45	−54.29	89.9	−161.7	−50
1st technique	134.2	−175.1	−60.2	−49.961	81.4	−148.5	−48.1
2nd technique (trial 1)	131.3	−174.1	−58.7	−48.68	79.5	−145.2	−48.3
2nd technique (trial 2)	130.7	−165.1	−58.2	−48.82	79	−144.7	−48.6
2nd technique (trial 3)	1.542	−194.6	−61.27	−50.17	80	−162	−73
2nd technique (trial 4)	137	−194.2	−61.74	−49.9	83	−151.7	−49.1
2nd technique (trial 5)	134.1	−189.7	−60.13	−48.98	81.4	−148.5	−48.2

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Table 2 Comparison between different techniques used to strengthen the two story frame.

Strengthening technique	Comparison parameters	Locations	Sections 1	2	3	4	5	6	7	8
Frame without Post tensioning	σ_N (MPa)	Interior side	13.1	−109	171	−144.9	−192.1	116.4	−201.8	89.8
		Exterior side	−65.7	36.7	−98.1	100.4	205.5	−102.1	94.3	−115
	σ_{sh} (MPa)	Interior side					75			
	Δ_b (mm)	Interior side						−25.9		
1st technique	σ_N (MPa)	Interior side	1.8	−99.3	152.8	−128.6	−170.2	82.3	−177.2	55.8
		Exterior side	−59.1	29	−90.3	86.4	182.1	−98	80.8	−106.7
	σ_{sh} (MPa)	Interior side					66			
	Δ_b (mm)	Interior side						−20.9		
	% σ_N	Interior side	86.3	8.9	10.6	11.2	11.4	29.3	12.2	37.9
		Exterior side	10	21	8	13.9	11.4	4	14.3	7.2
2nd technique	σ_N (MPa)	Interior side	−7.5	−100.9	116	−128	−171.1	81.1	−177.4	54.3
		Exterior side	−45.9	10.9	−88.8	62.1	184.9	−95.5	81.5	−105.4
	σ_{sh} (MPa)	Interior side					72			
	Δ_b (mm)	Interior side						−20.7		
	% σ_N	Interior side		7.4	32.2	11.7	10.9	30.3	12.1	39.5
		Exterior side	30.1	70.3	9.5	38.1	10	6.5	13.6	8.3

Table 3 Comparison between different techniques used to strengthen single frame subjected to dead and wind load.

Strengthening technique	$\sigma_{N,b}$		$\sigma_{sh,b}$	Δ_b	$\sigma_{N,c}$		Δ_L
	Tension (MPa)	Compression (MPa)	(MPa)	(mm)	Tension (MPa)	Compression (MPa)	(mm)
Frame without post tensioning	71.5	−59.5	19.1	42.24	72.5	−67.7	12.73
1st technique	61.1	−50.8	18.3	32.29	70.6	−66	12.46
2nd technique (trial 1)	74.7	−62.8	18.6	38.12	68.5	−63.8	13.19
2nd technique (trial 2)	74.5	−62.2	20	39.28	68.7	−63.4	13.25
2nd technique (trial 3)	74.7	−62.7	18.7	37.99	68.4	−63.7	13.14
3rd technique (trial 1)	63.9	−53.5	16.4	29.1	66	−61.2	12.46
3rd technique (trial 2)	61.8	−51.2	15.8	28.21	64.9	−80	10.25
3rd technique (trial 3)	62.3	−51.9	15.9	28.69	73	−68	11.85
3rd technique (trial 4)	61.7	−51.2	15.7	28.16	43.1	−66.1	10.84

7.2. Double bay frame

Table 1 shows the comparison between different techniques used to strengthen the double bay frame. The table shows the tension and compression bending stress ($\sigma_{N,b}$) of the beam, the beam's shear stress ($\sigma_{sh,b}$), maximum beam deflection (Δ_b), tension and compression bending stress of the column at the connection with the beam ($\sigma_{N,c,e}$), and the maximum normal stress at the column's mid height ($\sigma_{N,c,m}$). From the table it can be concluded that trial 2 of the 2nd technique gives the lowest reduction for different types of stresses and for the beam's deflection. It should be noted the comparison in Table 1 is based on applying primary loads plus cable post tension force equal 100 KN.

Fig. 8 shows the relation between different values of post tensioned force applied to the cable and the percentage of increase in the frame load capacity due to the effect of this load value. Fig. 8 shows a comparison between 1st technique and trial 2 of the 2nd technique. The comparison shows that trial 2 of the 2nd technique provides more strengthening effect and increases the frame load capacity compared to the 1st technique.

7.3. Two story frame

A comparison is made between the 1st technique results and the 2nd technique results. The key parameters of the comparison are shear stresses, normal stresses and the beam deflection at eight different locations (sections) in the beams and the columns. Fig. 9 shows the locations of different sections, where the comparison between the two techniques is done.

The comparison is indicated in Table 2, this comparison is done between different strengthening techniques and the frame without any strengthening. Table 2 shows the normal stresses (σ_N). shear stress (σ_{sh}) and the deflection (Δ_b). It should be noted that shear stress (σ_{sh}) and the deflection (Δ_b) are only given at Sections 5 and 6 respectively as these are the locations of maximum shear and deflections. The percentage of reduction in normal stresses (% σ_N) in the case of the two techniques is also provided in Table 2. From Table 2, it can be noticed that at each section the stress is shown for the interior and the exterior side of the section. The location of the interior and exterior side of each section is indicated in Fig. 9. It should be noted the comparison in Table 2 is based on applying primary loads plus cable post tension force equal 100 KN.

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It should be noted that the result of trial 1 and 2 of the 2nd technique have similar results and that is why only the result of trial two was presented. Trial 2 of the 2nd technique and was referred as 2nd technique. It can be concluded from Table 2 that the 1st techniques reduces stresses on the beam more than the 2nd technique. However, the 2nd technique reduces stresses on the column more than the 1st technique.

7.4. Wind load effect on single frame

Table 3 shows a comparison between all techniques that have been used to strengthen a single frame governed by the wind load effect. The applied post tensioned force equals 100 KN to all the cables and a uniform load equal to 4.32 KN/m' on the left column, 2.7 KN/m' on the right column and 2.52 t/m' on the beam as indicated in Fig 6. The table shows the tension and compression bending stress ($\sigma_{N,b}$) of the beam, the beam's shear stress ($\sigma_{sh,b}$), maximum beam deflection (Δ_b), tension and compression bending stress of the column ($\sigma_{N,c}$), and the lateral deformation of the columns (Δ_L).

From the comparison, It is obvious that the 1st technique gives more stress reduction for the beam. Trials (1 and 4) in the 3rd technique gives more stress reduction for the column and gives stress reduction in the beam close to that was given by the 1st technique. All Trials used to simulate the 2nd technique give nearly the same result. Trials (1 and 4) in the 3rd technique can be considered as the best techniques that can be used in strengthening single frame governed by wind load.

8. Conclusions

In this paper a detailed finite element (FE) analysis using ANSYS program (2005) is presented about strengthening steel frame using post tensioned cables. Three different type of steel frame is studied: simple frame, double bay frame and two story frame.

Different post tensioning techniques are used for each type of frame. These techniques are different from each other based on the profile and the location of the post tensioned cable. The technique that is used to strengthen each frame type was evaluated against the stress and deflection obtained from the FE model. Each frame type has specific technique that improves the load capacity of that frame; the technique that improves the load capacity for each frame type was identified and reported in the paper.

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.

Increasing the cable eccentricity will improve the load capacity of the frame. However, care should be taken as increasing the cable eccentricity much will decrease the roof clearance area.

Post tensioned cables can increase the load capacity of the frame by around 35% or more depending on the value of the post tensioned force and the cable eccentricity. Finally, strengthening frames using post tensioning cables can be used in repairing structures or as a main system of a newly designed frame.

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