Emerging Technologies and Engineering Journal

EngiScience Publisher

Research Article

Reviewing The Effectiveness of Different Methods of Applying Post-Tensioned Metal Straps (PTMS) In Enhancing the Flexural Strength of Normal Concrete Beams After Strengthening

Serwan Khwrshid Rafiq [1], **Wrya Abdullah** [1,*]

[1] Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaymaniyah, 46001, Iraq

*Corresponding Author: Wrya Abdullah, E-mail: wrya.faraj@univsul.edu.iq

Article Info

Article History

Received Mar 12, 2024

Revised Mar 30, 2024

Accepted Apr 01, 2024

Keywords

Metal straps

Bending

Strengthening Normal Concrete

Abstract

Concrete's strength and deformability can be enhanced by adding external lateral confinement. Several materials and confinement techniques have been investigated throughout the development of confined concrete, including Post-Tensioned Metal Straps (PTMS). This study compares three methods of using PTMS to strengthen normal Reinforced Concrete (R.C) beams in bending. First, the method of completely wrapping the beams longitudinally with metal straps is assessed. Secondly, the application of lateral metal straps is examined. Finally, the method of combining metal straps with steel channels is investigated. The assessment criteria included price, effort required for application, applicability of the method, strength enhancement, and ductility of the enhancement. It is concluded that wrapping the beam longitudinally with metal straps is the most cost-effective and easiest method. However, the use of metal straps with steel channels offers greater applicability, strength, and ductility, as it can be applied to any concrete beam. Finally, it is demonstrated that ANSYS can accurately model beams strengthened with metal straps, as evidenced by the good match between the failure modes of beams tested experimentally and analytically.

1. Introduction

When opposed to the commonly used fiber-reinforced polymer (FRP) a metal strap is a less expensive and more ecologically responsible option for externally confining concrete. Numerous works in the literature can be found to better understand the properties of a concrete element strengthened with a metal strap. For instance, several experimental and analytical research studies have been conducted on the compressive behavior of external steel-confined concrete.

To date, it is known that adding external lateral confinement to concrete can improve its strength and deformability. The lateral confinement applies restricting pressure to the concrete, which varies depending on the confinement material, method, and concrete dilatation. Various materials and confinement techniques, such as fiber-reinforced polymer (FRP) wraps/ tubes, FRP strips, steel jacketing, steel tubes, and steel straps, have been researched throughout the development of confined concrete.

Although FRP-confined concrete can show substantial strain-hardening after reaching its elastic limit, it cannot offer any warning signs before exploding [1, 2]. This is due to FRP's inherent brittleness while in tension. On the other hand, external metal-confined concrete can give enough warning signs and does not fail suddenly. External metal-based confinement also proved to be a viable alternative to high-priced FRP material due to its cheaper material cost, flexibility of approaches, and environmental friendliness. This study introduces the many forms of external metal-based confinement approaches before delving into the role of metal straps in structural characteristics.

Metal Strap Tensioning Technique (MSTT) is a restraint technique that uses strapping technology to strengthen building elements. The concrete will be contained and packed using metal hoops that are made of metal pre-tensioned and wrapped around concrete to trigger the impact of confinement.

According to previous studies, under certain conditions, MSTT can increase the structural performance of concrete [1, 3-5]. This is true in both axial compression [6-13] and flexural stresses [1, 3, 14-17]. The groundbreaking study on MSTT-confined concrete was carried out by Frangou et al. [6] when they employed a clamp clip, which is an inevitable part of the process. The process starts by wrapping the metal strap around the element and locking it in its place, then applying pressure and clipping it to seal it. During the sealing process, Moghaddam and his colleagues discovered a 30% prestress loss [18].

On top of that, the cross-sectional area of the metal hoops is reduced by the notches drilled on them, and as a result, the strength of the steel strap is reduced. The smaller cross-sectional area of the metal strap utilized in the anchoring method is a flaw in this technology. Metal hoops in the anchoring zone may fail prematurely due to having a smaller cross-sectional area. However, they proved their effectiveness even after the loss in strength. The strapping technology is used in the MSTT confinement technique to keep concrete contained and pre-tensioned to activate the concrete. Although prior research has revealed that pre-tensioning affects the strength and deformability of MSTT-confined concrete, the method has rarely been used in strengthening flexural members.

According to the studies on MSTT, this approach is capable of efficiently improving the strength and deformability of the concrete [7, 10, 11, 19]. The metal used in this process is not axially compressed. The amount of pre-tension stress can be adjusted to fit the confinement's application and to activate the confining action without causing significant concrete dilatation.

This paper compares several works on using metal straps to strengthen beams in flexure. This is particularly useful in guiding users on which one to use effectively based on the purpose of the usage. The comparison is made based on several aspects, which are the price, applicability, strength increase, efforts needed for the application, and ductility of different techniques of using the metal strap to strengthen normally reinforced beams in bending. This is found necessary as there are different types of works on using metal straps to increase flexural strength. Each of the methods has some practical advantages and disadvantages. It should be clear for the users which one to use in case of strengthening R.C beams. Therefore, this paper can be identified as a beneficial resource for those utilizing metal straps to strengthen R.C beams, serving as a practical guide.

2. Materials and Methods

Very few works can be found on using metal straps to strengthen normally reinforced beams in bending. This paper tries to compare all the works in the literature on using metal straps to strengthen normally reinforced beams.

Very few researchers have worked on strengthening normal R.C beams using PTMS. For instance, Yasser et al. [5] investigated reinforced concrete beams that had a deficiency in their lap splices. Their main focus was on the strength of the lap splices as they applied metal straps only in that region. As they studied a particular case of the bond strength between concrete and the main bar, it is not actually on strengthening; therefore, their paper is not regarded in the comparison of this paper. However, as their beam is strengthened in bending using metal straps, it is found necessary to mention. Their beam had a cross-sectional area of 150 mm by 250 mm, which is the width and height of the beam, as shown in Figure 1.

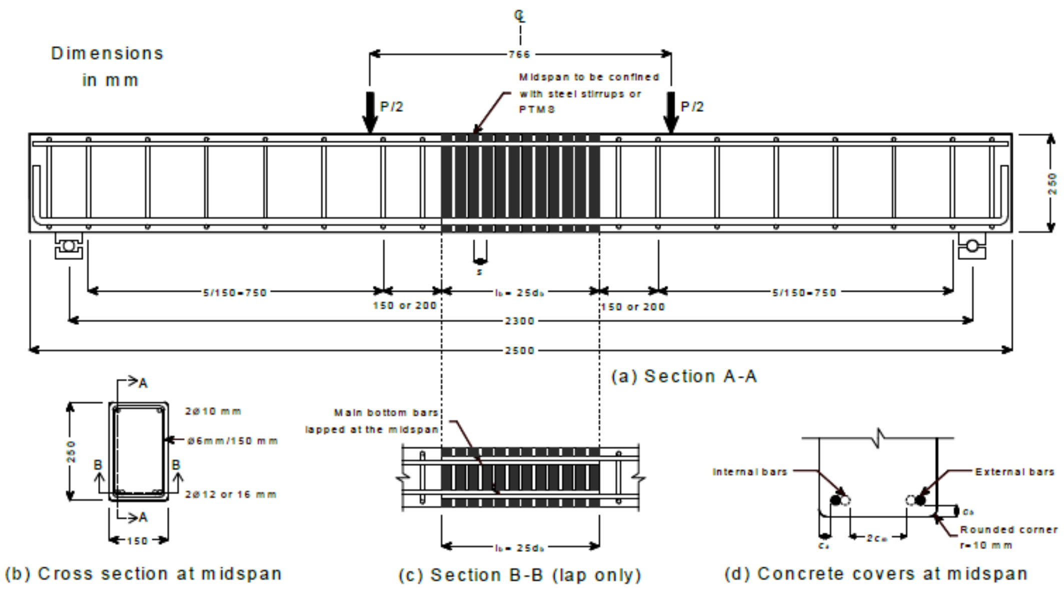

Figure 1. Beam details of the specimen used by Yasser [1]

As shown in Figure 1, the metal straps are applied in the form of fully wrapped around the beam laterally. They applied the technique to a minimal area in the middle of the beam, which makes it complex and challenging to compare it with the other ways of using metal straps.

Ma et al. [17] tested over reinforced beams using metal straps. The concrete they used is a high-strength concrete, so it is not regarded in the comparison of this paper. However, to illustrate the method of strengthening the beams in bending, metal straps are applied laterally, as shown in Figure 2.

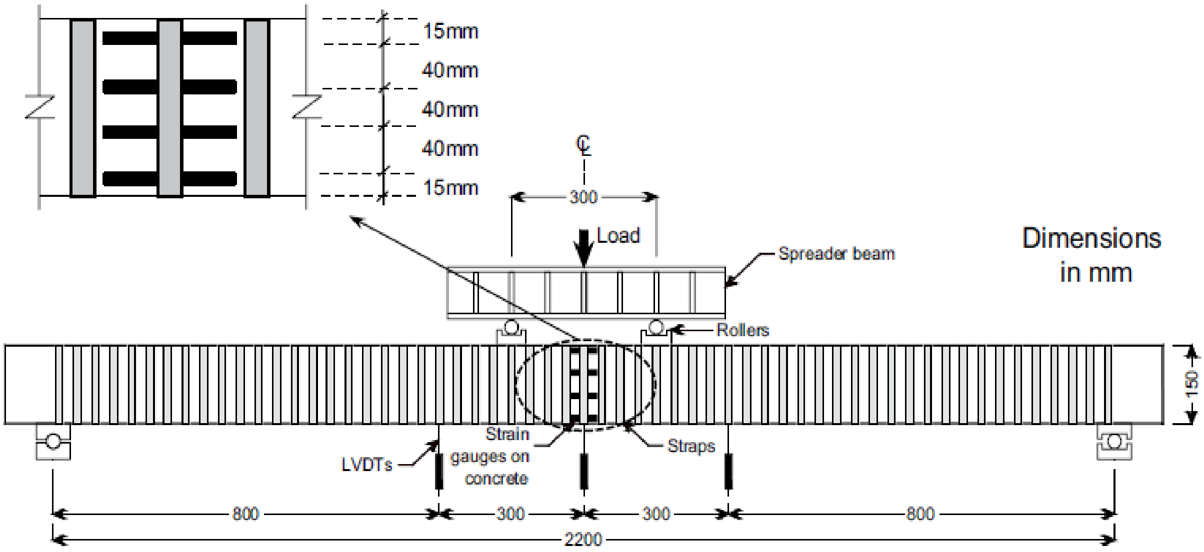

Figure 2. Beam details of the specimen used by Chau Ma et al. [15]

Sektik et al. [22] tested a beam till failure and then strengthened the beam using metal straps wrapped around the beam laterally, as shown in Figure 3. They found an improvement of 18.4 % and 29.3% in ductility.

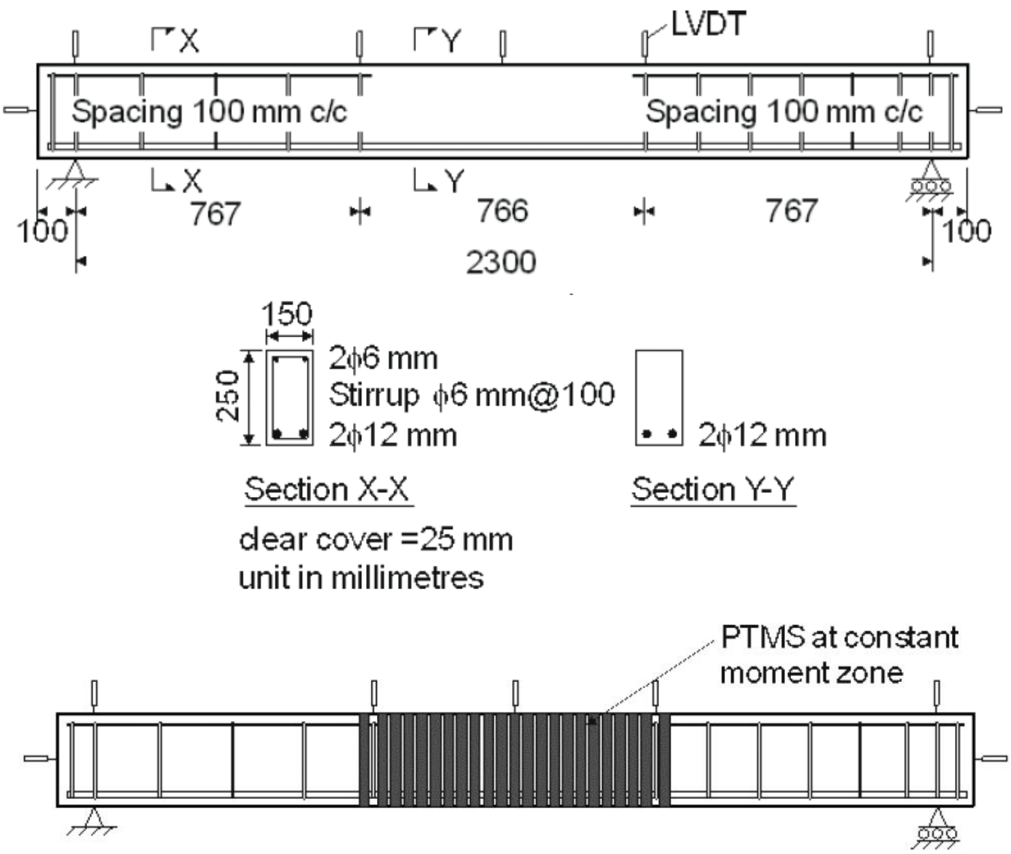

Figure 3. Beam details of the specimen used by Sektik et al. [22]

Abdullah & Rafiq [3] tested nine normal R.C beams, strengthening 7 of them using PTMS along with steel channels, changing the location of the channel and the number of straps as shown in Figure 4. Their beam had a cross-sectional area of 160 mm by 240 mm, which is width and height, respectively, with a clear span of 1900 mm. They used four-point loading for testing.

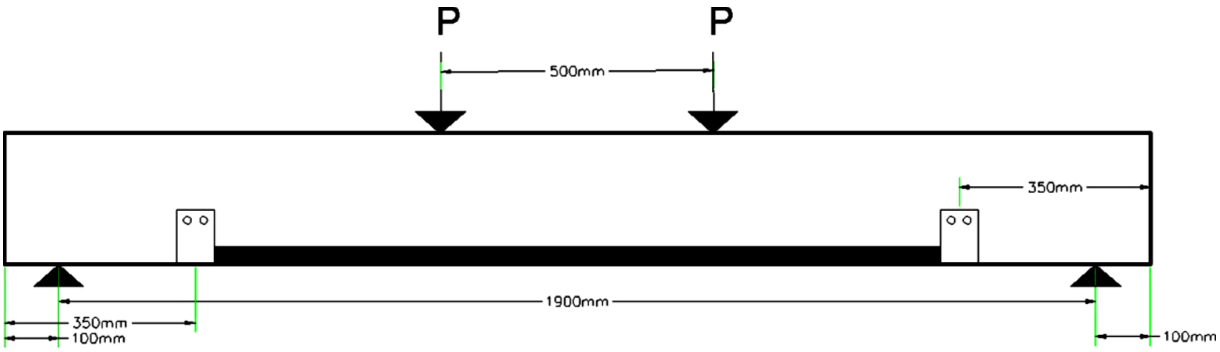

Figure 4. Beam details of the specimen used by Abdullah & Rafiq [3].

Abdullah et al. [20] tested four normal R.C beams strengthened with metal straps wrapped fully around the beam longitudinally. They tried to use metal straps to strengthen the beams in the form of fully wrapped longitudinally around the beam. The variables were the number of straps used fully around the beam, as shown in Figure 5.

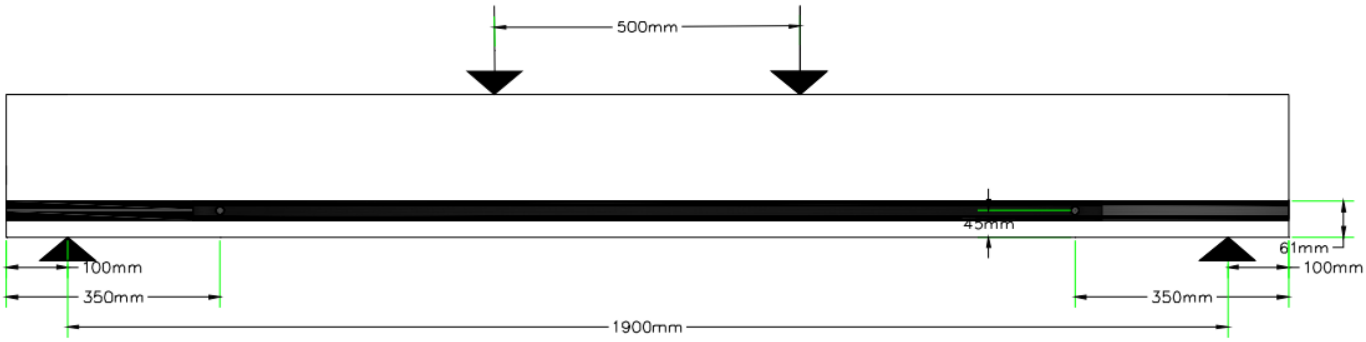

Figure 5. Beam details of the specimen used by Wrya et al. [20].

Others have worked on using MSTT to strengthen normal R.C beams in the shear [14, 21], but while this paper focuses on flexural strengthening, they have not been regarded as the work is on the shear and not bending.

The comparison is on the normal R.C beams, which are strengthened using MSTT in bending. Therefore, the three papers that share the properties close to each other but use three different methods of metal straps are considered in the comparison. Based on that, only three papers are compared. The details of the work are given in Table 1.

Table 1. Beam details of the comparison

Method No.	Authors	Beam Cross-Section (mm*mm)	Beam clear span (mm)	Type of MSTT usage
1	Sektik et al. 2019 and Imjai et al. 2020 [22]	150* 250	2300	Wrapped fully laterally
2	Abdullah & Rafiq 2021 [3]	160*240	1900	Wrapped with steel channels
3	Abdullah et al. 2021 [20]	160*240	1900	Wrapped fully longitudinally

Hereafter, methods 1, 2, and 3 will be used to describe each of the papers and their methods of application. Table 2 presents the details of the materials used in each method.

Table 2. Material details of the comparison

Method No.	Maximum aggregate size (mm)	Concrete compressive strength at 28 days (MPa)	Top rebar tensile strength (MPa)	Bottom rebar tensile strength(MPa)	Strap details	Yield strength of the metal strap (MPa)	Method of testing
1	19	30	392	392	25 mm *0.9 mm	850	4-point loading
2	10	27.4	500	504	32 mm * 0.8 mm	928	4-point loading
3	10	27.4	500	504	32 mm * 0.8 mm	928	4-point loading

3. Results and Discussions

The comparison is based on several categories that are important in selecting the proper method of applying metal straps.

3.1 Price

The price of the instruments needed for post-tensioning metal straps is the same for all three methods. The price of each item might be different from one country to another. The mentioned prices are from Iraq, where most of the materials are from China. So, the readers can calculate the prices based on their own countries and the materials needed for each method, which is explained in detail in this section. The technique needs a tensioner, an air compressor, and aluminum clips for sealing. These are fixed costs, but method 1 needs more clips as the metal straps will be applied laterally. A clip is needed at the end of the straps for anchoring. So, if method 1 and 2 are to be compared the way the straps appear in Figures 3 and 4, it can be seen that method 1 needs 23 clips while methods 2 and 3 need only two clips. The price of a clip is nearly $ 0.03 without shipping cost.

Additionally, the length of the metal strap affects the price of the technique. Method 1 needs more metal straps as they are used as external stirrups, and they will be wrapped around the beam. So, the length of one metal loop is nearly 1 m before tensioning it. In Figure 3, there are 23 loops, which means that 23 m is needed to strengthen the beam. While in methods 2 and 3, only 8 m of the strap is needed for the strengthening process. The price of the metal strap is approximately $1100 per ton without shipping costs, which is nearly 6000 m in length.

The factors that affect the weight of the metal strap are the cross-sectional area of the strap and its length. The cross-section of the metal straps in all three methods are nearly the same, which are 22.5 mm^2 in the first method and 25.6 mm^2 in methods 2 and 3, respectively. Method 1 uses fewer metal straps, which results in a cheaper option.

Some other costs will be added to use the metal straps with steel channels in method 2. As the channels are made up of steel, the cost is based on their weight. Therefore, the cross-section of the channel affects the price. For the ones used in method two, each channel will cost approximately $2. Therefore, $4 will be added to the price if two steel channels are used in strengthening the beams using steel channels. Also, the price of the bolts will be added when steel channels are used. So, four bolts are needed to anchor each of the steel channels, which costs nearly $2. Also, in applying the second method, as holes need to be drilled, a metal detector is needed to avoid having a hole in the rebar. A high-quality stud detector is needed, and another $50 is needed for the method.

To sum up, method 3 costs less based on the above compassion as fewer clips are needed, and the length is less than that in methods 1 and 2. Also, it does not need any holes and steel channels, nor does it need any bolts. Table 3 shows the extra cost each method needs apart from the essential costs. So, the price is minimal when method 3 is used compared to the other two methods. It is 68% and 80% less than that of the first method and the second method, respectively.

Table 3. An extra cost is needed for each of the strengthening methods after the essential instruments

Method of strengthening	**Total extra cost ($)**
Method 1	4.9
Method 2	7.5
Method 3	1.5

3.2 Efforts in application

Wrapping the straps fully around the beams is easier since it requires no preparation except for grinding the concrete off the edges of the beams; thus, methods 1 and 3 are simpler to apply. This is true as only the required length will be cut from the roll, and it will be wrapped around the beam and then tensioned using a tensioner. Method 2 needs the preparation of drilling holes and anchoring the steel channels. Also, detecting the place of the main rebars and the stirrups using a stud detector is another effort in using method 2 while this is not a problem in both method 1 and 3.

3.3 Applicability

In terms of practicality, method 2 is more practical than the other two methods that need holes to create the full wraps, as, in reality, the beams are attached to slabs and columns. So, the slabs should be drilled to house the straps safely, as shown in Figure 6.

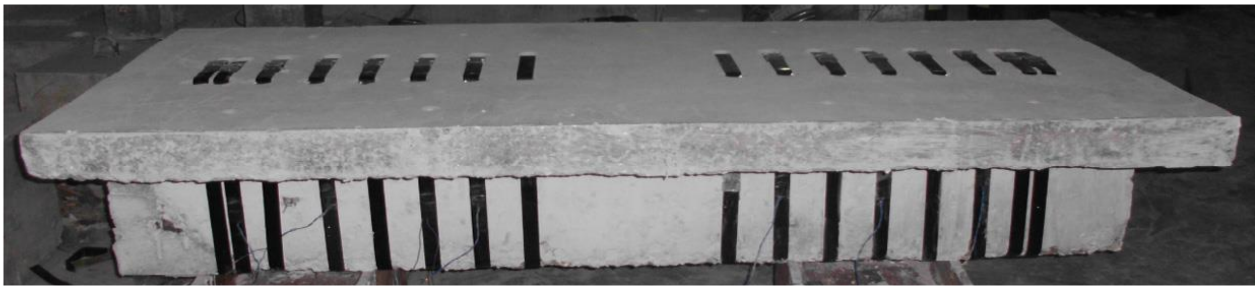

Figure 6. Slabs were drilled to create paths for the metal straps [21].

Another factor to consider in terms of practicality is the issue of finishing. This might be an obstacle in method 2 due to the presence of the bolts and steel channels. This might not be an issue in the other two methods, as there are no bolts. This is also true for method 3, as it needs holes at both ends of the beam to pass the metal straps through the holes and create a full wrap.

3.4 Strength enhancement.

As in Figure 7, there is not much difference between the strengthened beam (Phase II) with the first method of metal strap and the unstrengthened beam (Phase I), as the beam had been damaged in the first phase and then strengthened with metal straps. The maximum load-carrying capacity of the beam has not reached 70 kN after strengthening. So, there is no increase in the strength of the beam.

These (Control, 01, 55, 56, 73, 75, 76, and 101) are the designations of the tested beams by Abdullah & Rafiq [3], which are reinforced with various configurations of metal straps wrapped around steel channels. Because the steel channels were bolted to the beam faces, there was enough leeway for the straps to travel along with the deflection of the beams. The maximum load-carrying capacity using method 2 is more than 80 kN, which is nearly a 60% increase compared with the control specimen.

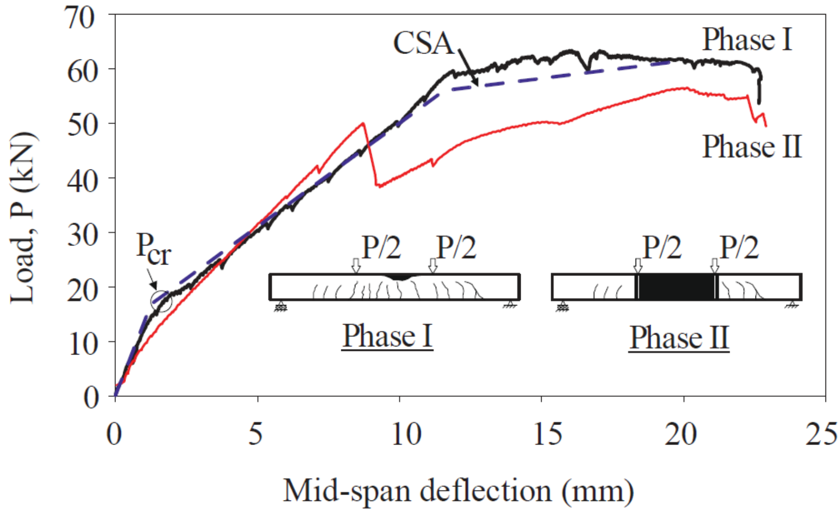

Figure 7. Load-deflection diagram of the beams used by Sektik et al. [22]

Figure 8 compares the fully wrapped PTMS-enhanced beams (counterparts 05 and 06) to their un-strengthen beams. These two beams are strengthened using method 3. Because beams 05 and 06 are post-tensioned around the beams, they have restricted the movement of the beam, and their longitudinal deflection capability is lower than that of the other beams. The straps were unable to tolerate the deflection of the beam due to a lack of elasticity. This was not the case with the beams reinforced with PTMS wrapped around the steel channels since the straps had room to travel along with the deflection of the beams. On the other hand, the load-bearing capacity can grow at the same pace.

This suggests that applying PTMS to steel channels rather than directly to the beam in a complete wrap form is more effective since the beam's ductility and strength may be enhanced.

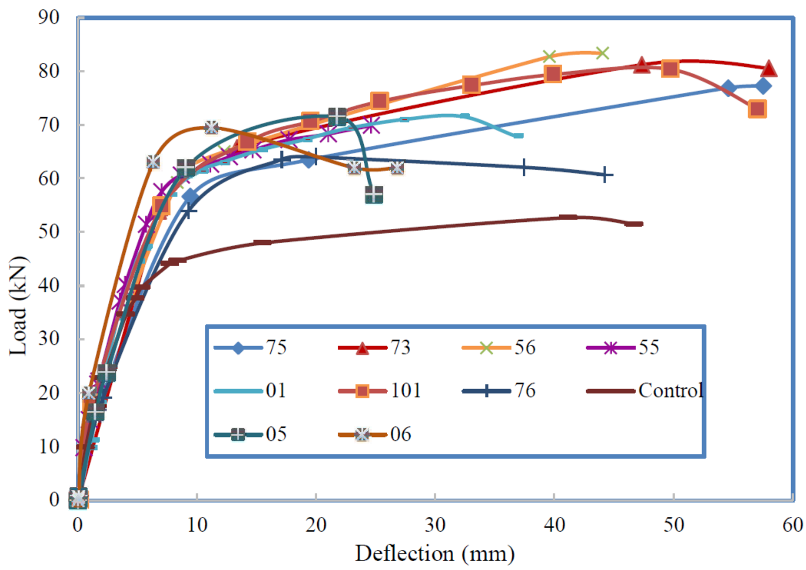

Figure 8. Load-deflection diagram of the beams used by Abdullah & Rafiq [3] and Abdullah et al. [20].

3.5 Ductility Enhancement

Method 2 increases the ductility the most as there is flexibility in applying the channels on the beams due to the existence of the holes and the tensioning force from the tensioner. This can be clearly observed from Figure 8. However, beams strengthened with method 3 can hold up to the deflection of 30 mm as the maximum compared to the maximum of nearly 60 mm for the beams strengthened with method 2. The ductility capacity is nearly twice as high as that of method 2 compared to method 3. The ductility capacity of method 1 can be seen in Figure 7, where there is less improvement in the ductility of the beams, as the ductility is nearly 23 mm in both strengthened and control specimens.

3.6 FEM verification

To study the mode of failure of the beams tested by Abdullah et al. [20], ANSYS Workbench 2019 R3 is used to model the beam. Two set of the beams are modeled, which are the control beam and the beam strengthened with one layer of the metal straps wrapped longitudinally around the beam. The compressive strength of the beam is 27.4 MPa. The yielding of the steel reinforcement is 504 MPa, and it is used in two different diameters: 10 mm for the main rebars and 8 mm for the stirrups.

The eight-node element type of Solid 186 is used to simulate the concrete. The crushing strain of 0.003 is used in the modelling of the concrete. Multilinear Kinematic Hardening is used to simulate the plasticity in each of the materials. A maximum size of 50 mm is used for meshing. Figure 9 shows the beam as it is modelled in the software.

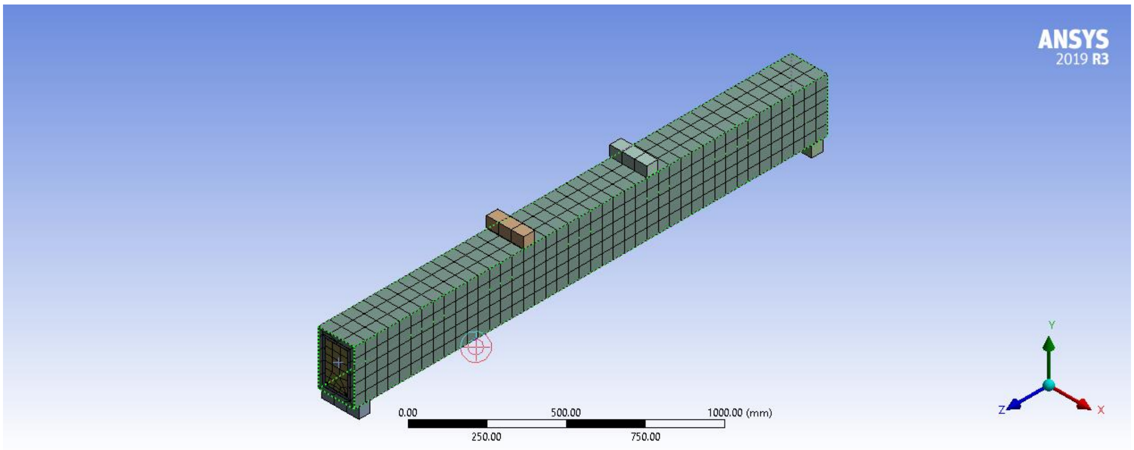

Figure 9. Modelled beam in ANSYS

A displacement control method is used to test the beams. Two loading plates are modelled for applying the displacements. Two bearing plates are modelled to act as supports, and their displacements are specified to be zero at the y-axis and free at the x and z axes. In the analysis, large deflection was allowed to occur. After testing the control beam, it was found that the beam could sustain the maximum deflection of 10 mm from the loading plates. However, when strengthened using metal straps, the weak point changes to the straps, and the straps explode at the edge of the beam, as shown in Figure 10. This aligns with what has been reported by the authors, as the straps ruptured at the edge of the beams. The tension inside of the straps is simulated by using the bolt pre-tension load of 25 kN, which represents the stress of nearly 980 MPa, which is the maximum strength of the straps. The solution was not converging as a result of the failure in the metal straps. This result shows that with using PTMS wrapped fully around the beam longitudinally, the deflection capacity of the beam would be restricted as the beam would fail in the metal straps.

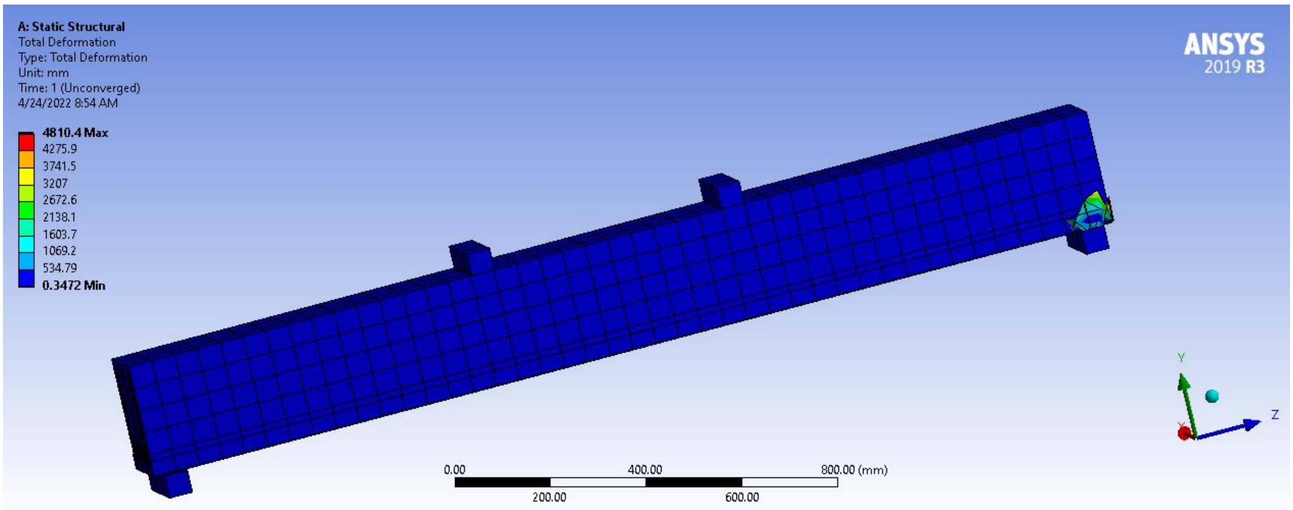

Figure 10. Failure of the straps at the edge of the beam.

4. Conclusions

This paper evaluates three effective strategies for enhancing the bending strength of normal R.C beams. The methods explored include fully wrapping the beams with metal straps longitudinally, wrapping them laterally, and utilizing metal straps in conjunction with steel channels. Based on the findings, several conclusions emerge:

Wrapping the beam longitudinally with metal straps is identified as the most cost-effective method, costing significantly less than both lateral wrapping and the use of metal straps with steel channels. Specifically, longitudinal wrapping is 68% and 80% cheaper than the other two methods, respectively.

In terms of effort, applying metal straps around the beams fully, whether longitudinally or laterally, is simpler compared to integrating them with steel channels. This simplicity could be particularly advantageous in projects where labor constraints are a consideration.

When considering the applicability to various concrete beam configurations, the combination of metal straps with steel channels stands out. This method proves to be the most versatile and capable of being applied to any concrete beam, thereby offering broader practical utility.

The strength enhancement offered by each method varies, with the use of steel channels and metal straps providing up to a 60% increase in beam strength. This improvement drops significantly when the beams are fully wrapped longitudinally, and there is no observed strength enhancement with full lateral wrapping. This highlights the superior efficacy of combining metal straps with steel channels in terms of strength enhancement.

Ductility, or the ability of the beams to undergo significant deformation before failure, sees a remarkable improvement of 100% when metal straps are used alongside steel channels. This increase in ductility is crucial for seismic resilience and overall structural durability.

The study also validates the effectiveness of using ANSYS for modeling beams strengthened with metal straps. The simulation results closely match the experimental outcomes, particularly in terms of failure modes. This accuracy underscores the utility of ANSYS as a tool for predicting the performance of strengthened R.C beams, facilitating more efficient design and analysis processes.

Overall, while each method has its merits, the combination of metal straps with steel channels emerges as the most advantageous in terms of strength, ductility, and applicability, albeit with a higher cost and effort compared to solely wrapping the beams.

Declaration of Competing Interest: The authors declare that they have no known competing interests.

References

[1] Y. Helal, R. Garcia, K. Pilakoutas, M. Guadagnini, and I. Hajirasouliha, "Strengthening of short splices in RC beams using Post-Tensioned Metal Straps," *Materials and Structures/Materiaux et Constructions*, vol. 49, no. 1–2, pp. 133–147, 2016, doi: 10.1617/s11527-014-0481-6.

[2] R. Garcia *et al.*, "Shake Table Tests on Deficient RC Buildings Strengthened Using Post-Tensioned Metal Straps Reyes," in *Seismic Evaluation and Rehabilitation of Structures*, 1st ed., A. Ilki and M. N. Fardis, Eds. Switzerland: Springer, 2014.

[3] W. Abdullah and S. K. Rafiq, "Flexural strengthening of beams using posttensioned metal straps fully wrapped around steel channels anchored to normal steel reinforced concrete beams," *PLoS One*, vol. 16, no. 6 June, 2021, doi:

10.1371/journal.pone.0253816.

[4] R. Garcia *et al.*, "Full-Scale Shaking Table Tests on a Substandard RC Building Repaired and Strengthened with Post-Tensioned Metal Straps," *Journal of Earthquake Engineering*, vol. 18, no. 2, pp. 187–213, Feb. 2014, doi: 10.1080/13632469.2013.847874.

[5] Y. Helal, "Seismic Strengthening of Deficient Exterior RC Beam-Column Sub-assemblages using Post- tensioned Metal Strips," The University of Sheffield, 2012.

[6] M. Frangou, K. Pilakoutas, and Dritsos S., "Structural repair/strengthening of RC columns," *Construction and Building Materials*, vol. 9, no. 5, pp. 1–8, 1995.

[7] C. K. Ma, R. Garcia, S. C. S. Yung, A. Z. Awang, W. Omar, and K. Pilakoutas, "Strengthening of pre-damaged concrete cylinders using post-tensioned steel straps," *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, vol. 172, no. 10, pp. 703–711, 2019, doi: 10.1680/jstbu.18.00031.

[8] W. A. Abdullah and S. K. Rafiq, "Compressive Strength of Uncured Concrete Cylinders Fully Wrapped with Post-Tensioned Metal Straps (PTMS).," *Journal of Engineering Research*, Nov. 2021, doi: 10.36909/jer.13371.

[9] M. Yaqub and C. G. Bailey, "Repair of fire damaged circular reinforced concrete columns with FRP composites," UK, 1, 2011.

[10] C. L. Chin, C. B. Ong, J. Y. Tan, C. K. Ma, A. Z. Awang, and W. Omar, "Confinement-concrete interaction in pre-tensioned partial steel-confined concrete," *Structures*, vol. 23, no. August 2019, pp. 751–765, 2020, doi: 10.1016/j.istruc.2019.12.006.

[11] C. Chin, C.-K. Ma, A. Z. Awang, W. Omar, and A. B. H. Kueh, "Stress-strain evaluation of steel-strapped high-strength concrete with modified self-regulating end clips," *Structural Concrete*, vol. 19, no. 4, pp. 1036–1048, Aug. 2018, doi: 10.1002/suco.201700134.

[12] C. K. Ma, A. Z. Awang, and W. Omar, "Slenderness effect and upper-bound slenderness limit of SSTT-confined HSC column," *International Journal of Structural Engineering*, vol. 5, no. 3, pp. 279–286, 2014, doi: 10.1504/IJSTRUCTE.2014.063048.

[13] C. K. Ma, A. Z. Awang, W. Omar, and L. Maybelle, "Experimental tests on SSTT-confined HSC columns," *Magazine of Concrete Research*, vol. 66, no. 21, 2014, doi: 10.1680/macr.14.00065.

[14] W. Abdullah and S. Rafiq, "Experimental work on Shear Strengthening of Beams Using Post- Tensioned Metal Straps Wrapped Around Steel Plates Anchored to Normal Steel Reinforced Concrete Beams," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, pp. 1–43, 2021.

[15] C. K. Ma, A. Z. Awang, W. Omar, M. Liang, S. W. Jaw, and M. Azimi, "Flexural capacity enhancement of rectangular high-strength concrete columns confined with post-tensioned steel straps: experimental investigation and analytical modelling," *Structural Concrete*, vol. 17, no. 4, pp. 668–676, 2016, doi: 10.1002/suco.201500123.

[16] T. Chaudat, C. Garnier, and S. Poupin, "Ecoleader project no.2- seismic tests on a reinforced concrete bare freame with retroffitng - tests report," France, 2005.

[17] C. K. Ma, A. Z. Awang, R. Garcia, W. Omar, and K. Pilakoutas, "Behaviour of over-reinforced high-strength concrete beams confined with post-tensioned steel straps – an experimental investigation," *Structural Concrete*, vol. 17, no. 5, 2016, doi: 10.1002/suco.201500062.

[18] H. Moghaddam, M. Samadi, K. Pilakoutas, and S. Mohebbi, "Axial compressive behavior of concrete actively confined by metal strips; Part A: Experimental study," *Materials and Structures/Materiaux et Constructions*, vol. 43, no. 10, pp. 1369–1381, 2010, doi: 10.1617/s11527-010-9588-6.

[19] M. Chau-Khun, A. Z. Awang, W. Omar, K. Pilakoutas, M. M. Tahir, and R. Garcia, "Elastic design of slender high-strength RC circular columns confined with external tensioned steel straps," *Advances in Structural Engineering*, vol. 18, no. 9, pp. 1487–1499, 2015, doi: 10.1260/1369-4332.18.9.1487.

[20] W. Abdullah, A. Omar, and S. Rafiq, "Experimental Work on Using Fully Wrapped Post-Tensioned Metal Straps Around

Normal Steel Reinforced Beams to Increase Flexural Strength of R . C Beams Experimental Work on Using Fully Wrapped Post-Tensioned Metal Straps Around Normal Reinforced Concrete B," no. August, 2021, doi: 10.17656/sjes.10147.

[21] Y. Yang, S. Feng, Y. Xue, Y. Yu, H. Wang, and Y. Chen, "Experimental study on shear behavior of fire-damaged reinforced concrete T-beams retrofitted with prestressed steel straps," *Construction and Building Materials*, vol. 209, pp. 644–654, 2019, doi: 10.1016/j.conbuildmat.2019.03.054.

[22] T. Imjai, M. Setkit, R. Garcia, and F. P. Figueiredo, "Strengthening of damaged low strength concrete beams using PTMS or NSM techniques," *Case Studies in Construction Materials*, vol. 13, p. e00403, Dec. 2020, doi: 10.1016/j.cscm.2020.e00403.