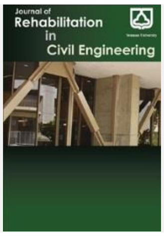

Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

Computational and Experimental Study on Comparing the Methods of Retrofitting the Steel Lattice Tower under the Effect of Wind Load

Hossein Sadeghi [1,*]; Mohammad Khalili Nejad [2]; Mohsen Sadeghi [3]

1. Assistant Professor, Department of Civil Engineering , Damghan Branch, Islamic Azad University, Damghan, Iran
2. Master's Student, Department of Civil Engineering, Shahrood Non-Profit University, Shahrood, Iran
3. Ph.D., Department of Electrical Engineering, Shahrood University of Technology, Shahrood, Iran

* Corresponding author: *Hossein.Sadeghi@iau.ac.ir*

ARTICLE INFO

Article history:
Received: 27 March 2024
Revised: 14 September 2024
Accepted: 01 November 2024

Keywords:
CFD;
Retrofitting;
Steel lattice tower;
Wind pressure coefficients.

ABSTRACT

One of the common structures in power transmission towers is the steel lattice towers with the bolted connection type, which can be vulnerable to wind loads due to their low weight and high height. Due to the change in the wind design codes and the placement of new devices on these towers, retrofitting is inevitable. In this research, firstly, the effect of wind load on the mentioned structure has been investigated, in calculating the wind force on the structure, the coefficient that is related to the geometry of the structure is the CP coefficient. Wind pressure coefficients (CP) were obtained using Ansys software based on the structure's computational fluid dynamics (CFD) method. Based on the CFD analysis, the maximum positive pressure coefficient (pressure) and the maximum negative pressure coefficient (suction) are obtained as +1 and -1.2, respectively. Using the computational analysis of the structure under the effect of wind, it was observed that under the effect of wind load, the factor of instability of the structure can be the buckling of the compressive members. Therefore, seven models were studied under buckling test. The M1 model served as the base model consisting of a single angle, while the M2 to M7 models represented reinforced variations of the original design. Experimental and numerical results revealed that adding an angled connection along a section of the primary member's length (M4 model) can increase the member's resistance by 38%.

E-ISSN: 2345-4423

How to cite this article: Sadeghi, H. , Khalili Nejad, M. and Sadeghi, M. (2025). Computational and Experimental Study on Comparing the Methods of Retrofitting the Steel Lattice Tower under the Effect of Wind Load. Journal of Rehabilitation in Civil Engineering, 13(3), 43-53. https://doi.org/10.22075/jrce.2024.33634.2030

1. Introduction

Steel lattice towers are a prevalent type of power transmission structure. However, with changes in wind design codes and the need to accommodate new devices on these towers, designers actively seek retrofitting solutions for such structures. Although the wind-exposed surface area of this type of structure is small, the tower's light weight makes it vulnerable to wind load. Therefore, wind load is typically considered the dominant lateral load for this type of structure. The ensuring the structural safety of the Transmission tower- under severe wind hazards is a primary concern for designers, owners, managers, and society. Figure 1 illustrates an example of a tower collapse under the effect of wind load.

Fig. 1. Collapse of steel lattice tower due to wind load (Sindh, April 2022).

Due to their truss behavior in this type of structure, compression members are often susceptible to damage. Therefore, methods for strengthening these compression members are being considered.
A transmission tower made with angle steel is cost-effective and simple to assemble. Angle steel towers are particularly economical for shorter spans and lower tower heights. Transmission tower-line systems are essential for providing reliable service, and ensuring the structural safety of the towers is crucial for maintaining the functionality of the systems. Steel lattice towers have been extensively used worldwide as an essential component of power transmission networks. Typically, these towers are built using equal leg angle section members and bolted connections of the bearing type. Depending on the magnitude of the conductor and environmental loads, as well as the geometric constraints of the transmission line, significant axial forces may occur in the primary members at lower parts of the tower. This can necessitate using built-up sections at these locations [1]. Various factors, including the details of connections, influence the behavior of towers. In transmission towers, spatial connections with multiple gusset plates are commonly used [2] . An effective way of increasing the carrying capacity of a tower is to reinforce its core leg members by attaching additional elements with bolted connections [3]. Bearing-type bolted connections are employed in lattice structures, such as lattice transmission lines (TL) and communication towers, to connect steel angle sections [4]. Research has been conducted on the influence of wind on these structures [5–7]. Due to the increasing collapse of transmission towers due to high winds, several retrofitting techniques on diagonal braces have been proposed [8–10].

Fig. 2. Retrofitting system and the retrofitted sub-assembly. [11].

Studies have been conducted in transmission tower connections; however, details such as joint eccentricities, rotational stiffness, and slippage are often overlooked in fragility analyses due to the associated complexity of modeling and considerable computational effort [11–13]. Steel lattice transmission towers are constructed through the bolted assembly of various sizes of angle steel members, and joint slip is inevitable. Ignoring this slip, a common practice in transmission tower design engineering, can overestimate the axial stiffness of bolted joints. Therefore, several studies have investigated joint slippage models [14,15]. Although advancements have been achieved in studying members under axial pressure, buckling remains challenging in analyzing and designing compression steel structural members[16,17]. In buckling behavior, a physics-informed neural network (PINN) is proposed to analyze the nonlinear buckling behavior of a 3D network[18–20]. The research innovatively compares the methods of retrofitting power transmission towers and provides wind pressure coefficients for this type of structure.

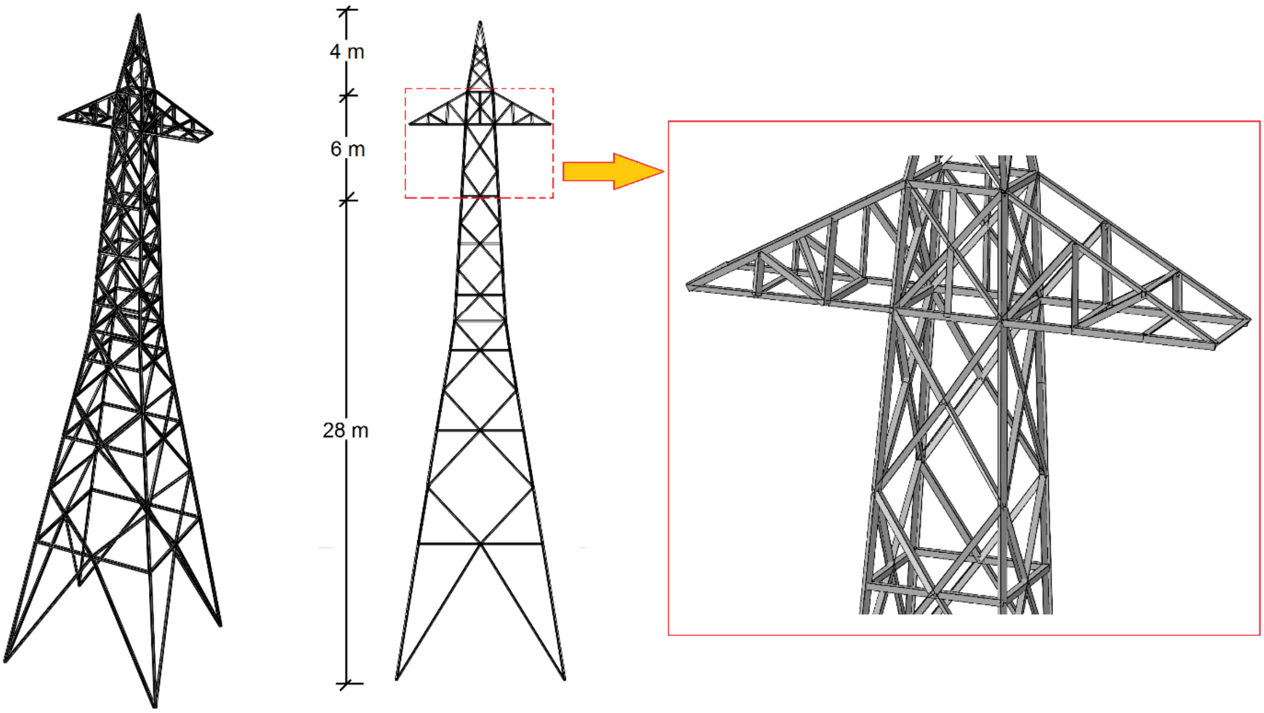

Fig. 3. Geometrical details of the steel lattice towers model used in the CFD analysis.

2. CFD analysis

In this study, first has been investigated the impact of wind load on the tower structure using Ansys software and a computational fluid dynamics approach. Fig. 3 illustrates the structure modeled in Ansys software. The software also modeled a part of the tower structure, and the wind pressure coefficients on this structure were obtained. The wind tunnel model depicts the boundary conditions and the tower mesh, as illustrated in Fig. 4.

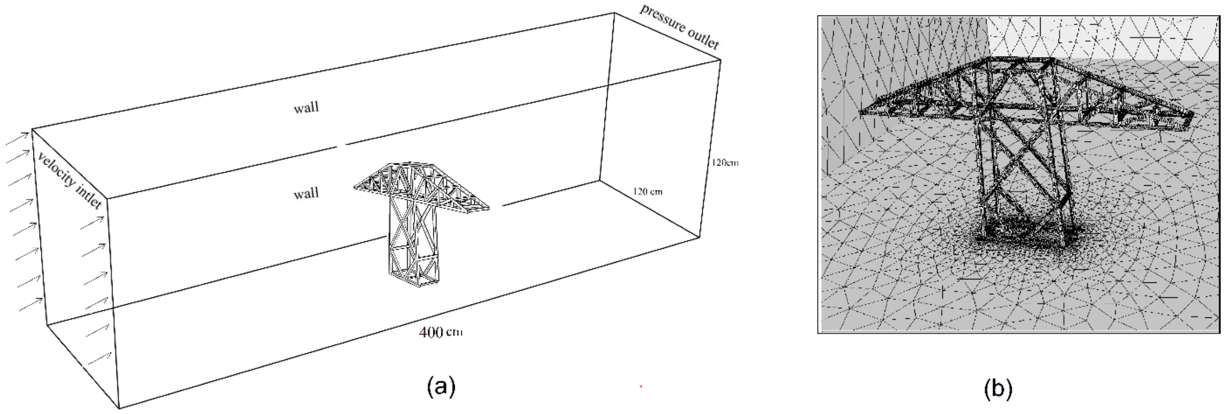

Fig. 4. (a) Boundary conditions of wind tunnel modeling in ANSYS software, (b) mesh pattern on tower.

Equation (1) demonstrates the wind speed applied to the wind pressure coefficient; CP is a dimensionless parameter. Where (P- P∞) represents the instantaneous pressure difference between the dome surface pressure and a reference pressure in the wind tunnel. ρ And V are the density and velocity of air, respectively.

$$C_P = \frac{P - P_\infty}{0.5\rho V^2} \quad (1)$$

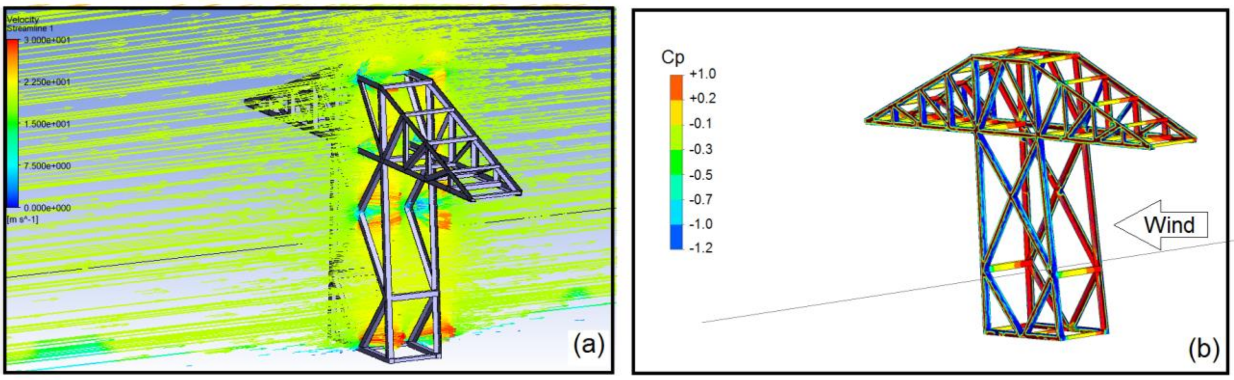

Fig. 5. (a), Streamlines around the tower, (b) Distribution of wind pressure coefficients on the tower.

Fig. 5 displays the streamlines around the tower and wind pressure coefficient (Cp) contours on the structure. The wind speed entering the tunnel is assumed to be 20 m/s.

Fig. 6 depicts the structure's deformation due to wind load and the tower's first-mode shape. As illustrated in Figure 6b, the tower's first-mode shape occurs due to the buckling of one of the compression members. Fig. 6 shows the deformation of the structure under the effect of wind load, and the first mode shape of the tower is also presented. As seen in Fig. 6b, the first mode shape of the tower is caused by the buckling of one of the compression members.

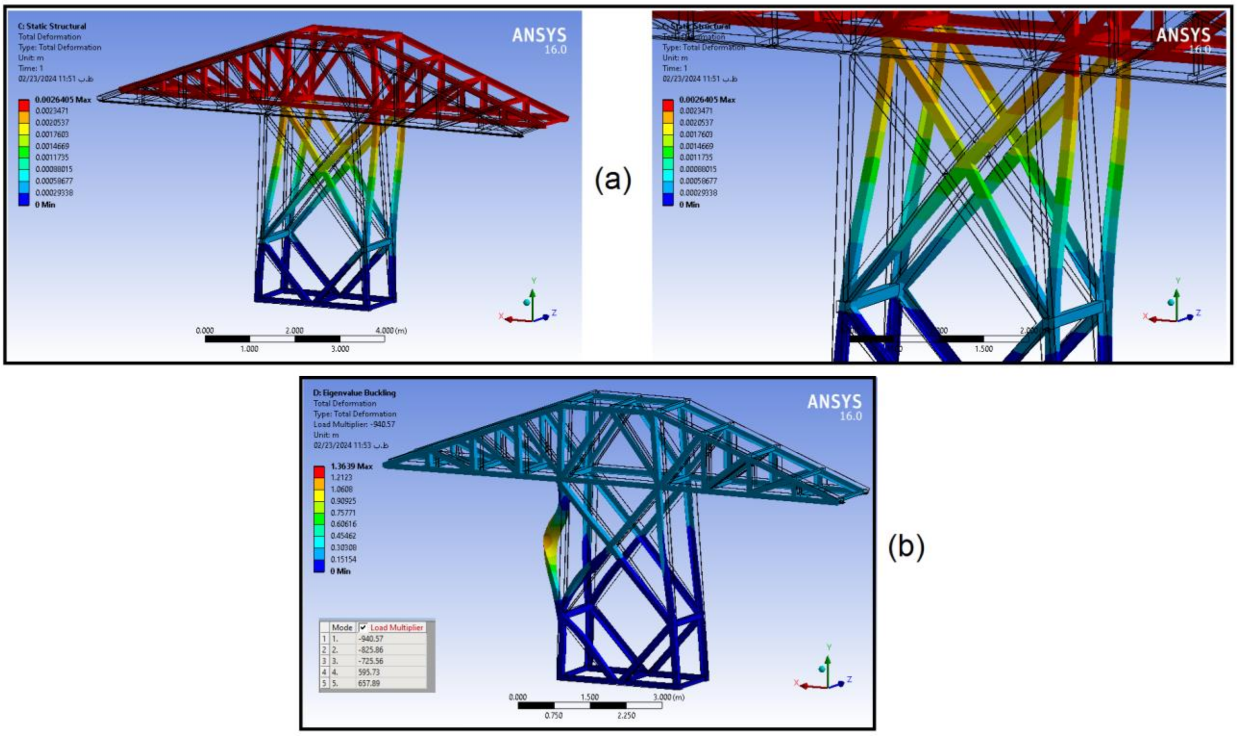

Fig. 6. (a) Contour deformation of the tower structure due to wind load, (b) the first mode shape of the tower.

3. Experimental research

Seven models depicted in Fig. 7 are evaluated to find easy solutions for strengthening the Compression members. The models are made from an L30x30x3 with a length of 40 cm. The connection of the two ends of the members in the experiment and numerical modeling is considered a pin connection.

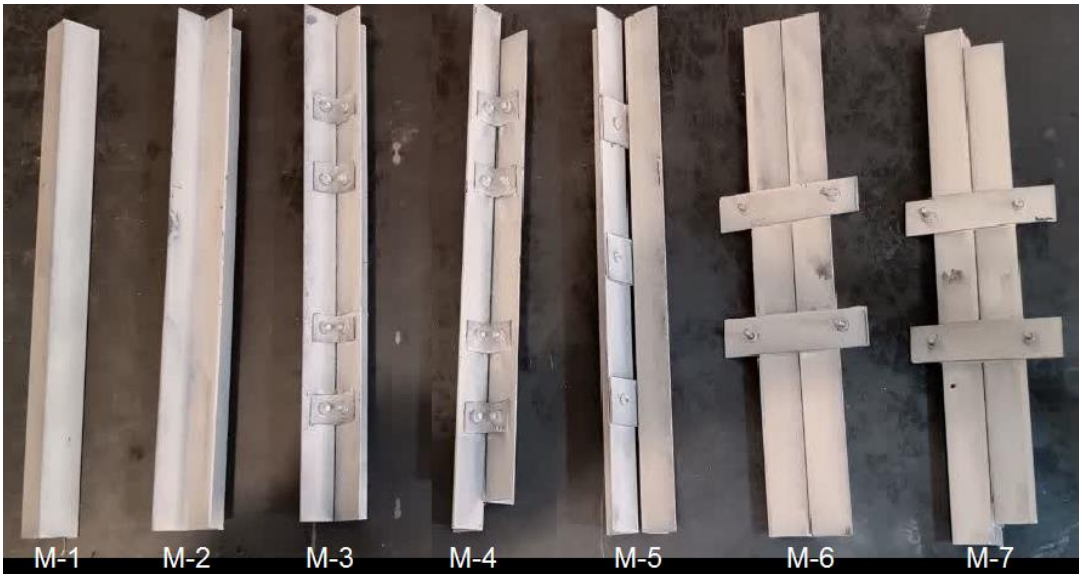

Fig. 7. Geometrical details of the models made in the buckling test.

Figure 8 displays the details of the models used in the experiment and numerical modeling. Model M1 is a single angle representing an unreinforced member of the tower. The M2 model has two Angles, and welding connects the reinforcing angle to the primary member.

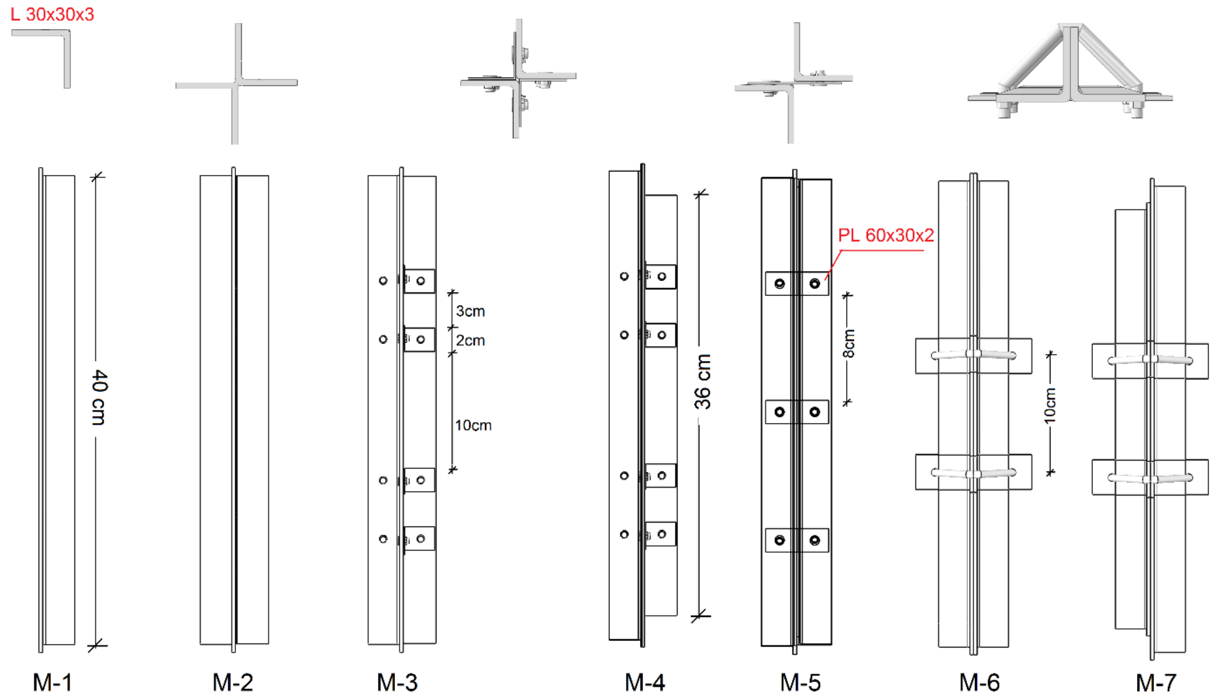

Fig. 8. Geometric details of the models used in the FE analysis and experimental test.

In the M3 model, the additional angle is connected to the primary member using 4 connecting devices, as illustrated in Fig. 8. The M4 and M3 models are similar; the only difference is the reinforcement angle's length. In the M4 model, the applied load is applied only to the primary member, but in the M3 model, the load is applied to both angles. In the M5 model, two Angles are connected by three plates. The M6 angle reinforcement is connected to the primary member using two clamps. The M7 model is similar to the M6 model, but in the M7 model, the force is only applied to the primary member. A reinforcing angle with a shorter length is also connected to the primary member.

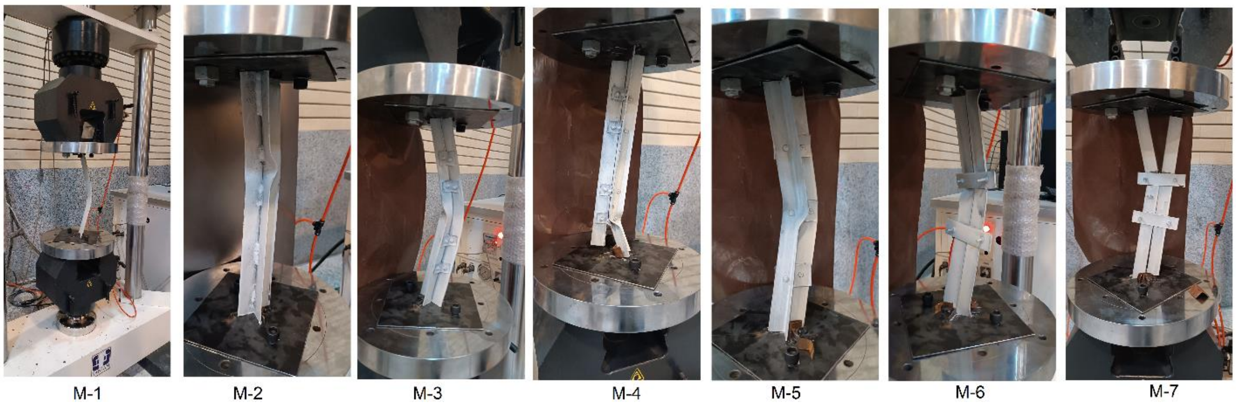

Fig. 9. Failure modes of the models.

Fig 9 displays the failure modes of the tested models. Fig 10 illustrates the force-displacement diagram of the M2 model compared to the M1 and M3 models. The maximum load of the M1 model is 33.8 KN, while the maximum load of the M2 and M3 models equals 100 and 84 KN, respectively. While it is evident that the M2 model might be the best option, we have chosen other models because most connections in transmission towers are of the bolted connection type. Another reason for selecting the reinforcing angle connection to the primary member is its simplicity.

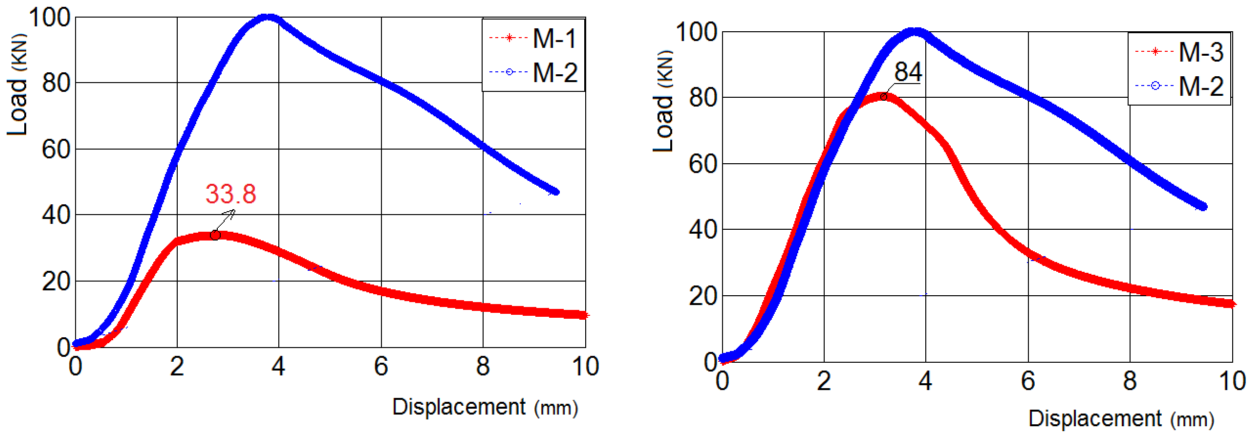

Fig. 10. Comparison of the load-displacement diagram of M2 model with models M1 and M3.

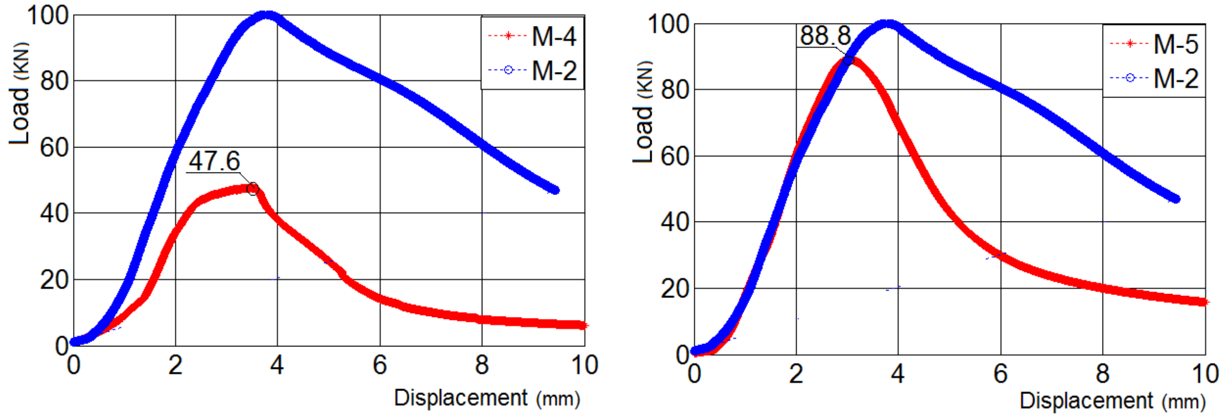

Fig.11. Comparison of the load-displacement diagram of M2 model with models M4 and M5.

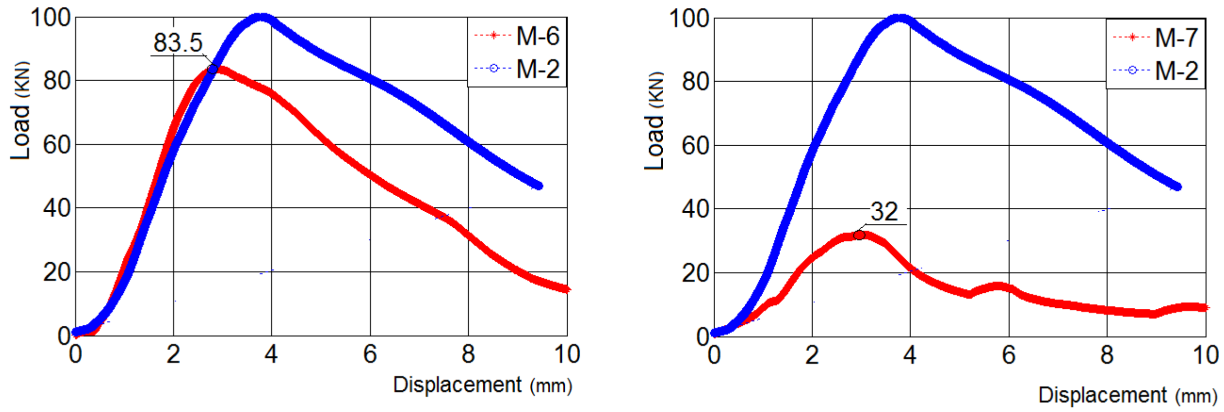

Fig. 12. Comparison of the load-displacement diagram of M2 model with models M6 and M7.

According to Fig. 11, the maximum load of the M4 model is 47.6 KN, which indicates a 43% decrease in load compared to the M3 model, which has a maximum load of 84 KN. Fig. 12 demonstrates the effect of angle reinforcement using clamps. Comparing the M2 model with the M7 model indicates that strengthening part of the primary member's length with clamps (similar to the M7 model) does not increase the single angle strength. Fig. 13 illustrates the difference between the tower member's reinforcement with one angle throughout (M3 model) and the primary member's reinforcement with a shorter angle (M4 model). The bearing capacity increases by 68% in the M3 model compared to the M4 model. Furthermore, the reinforcing member must also be connected to the connection plate.

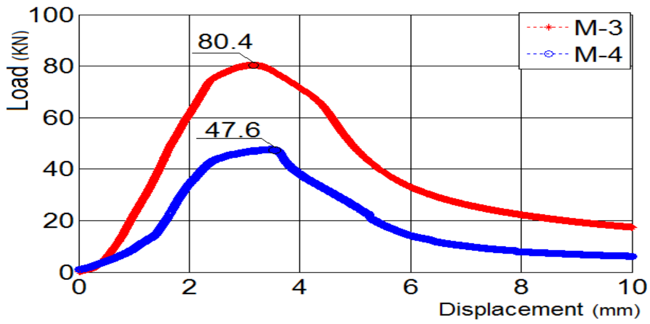

Fig. 13. Comparison of the load-displacement diagram of models M3 and M4.

Fig. 14 demonstrates the effect of using clamps to connect the reinforcing angle to the primary member. When the reinforcing member is fully connected to the primary member, the performance is appropriate, while connecting the reinforcing member using a clamp in part of the length of the primary member (model M7) does not effectively increase the load.

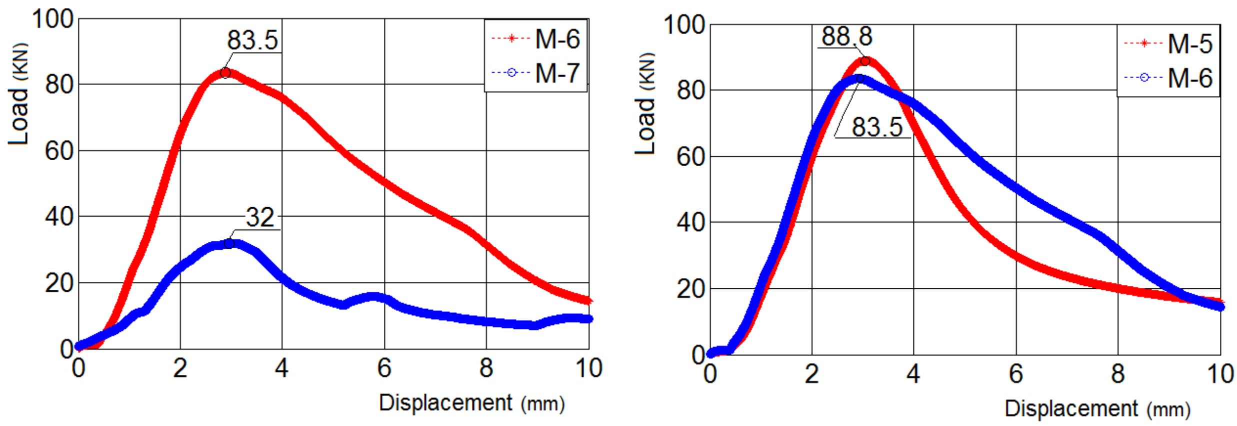

Fig. 14. Comparison of the load-displacement diagram of M6 model with models M5 and M7.

4. Numerical modeling

Figure 15 demonstrates the failure modes of models M1 to M7. These results are obtained from numerical modeling using Abaqus software. The Static Riks analysis model is used in numerical modeling. This analysis method is capable of analyzing post-buckling behavior as well as the behavior of structures that have local or global instability.

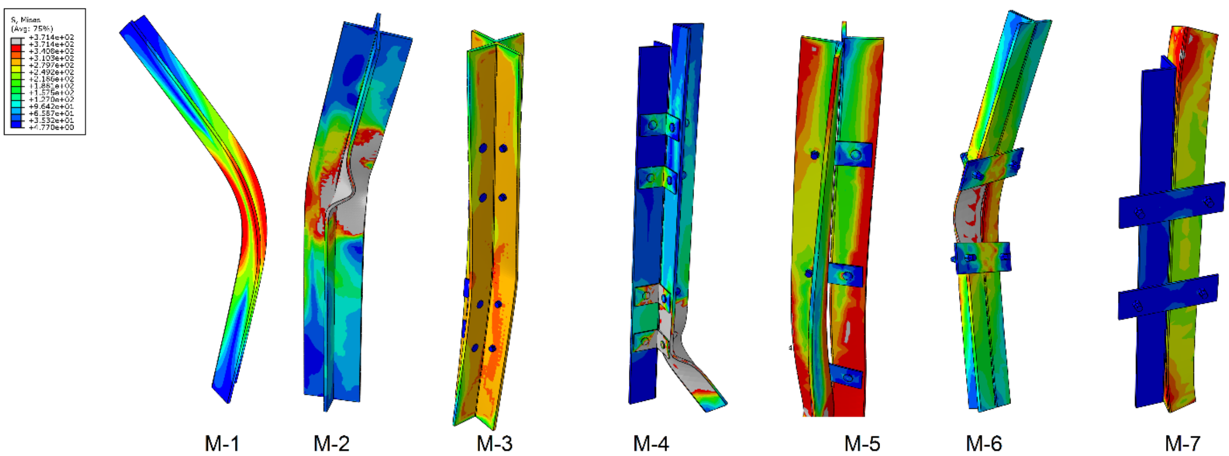

Fig. 15. Failure pattern of FE models.

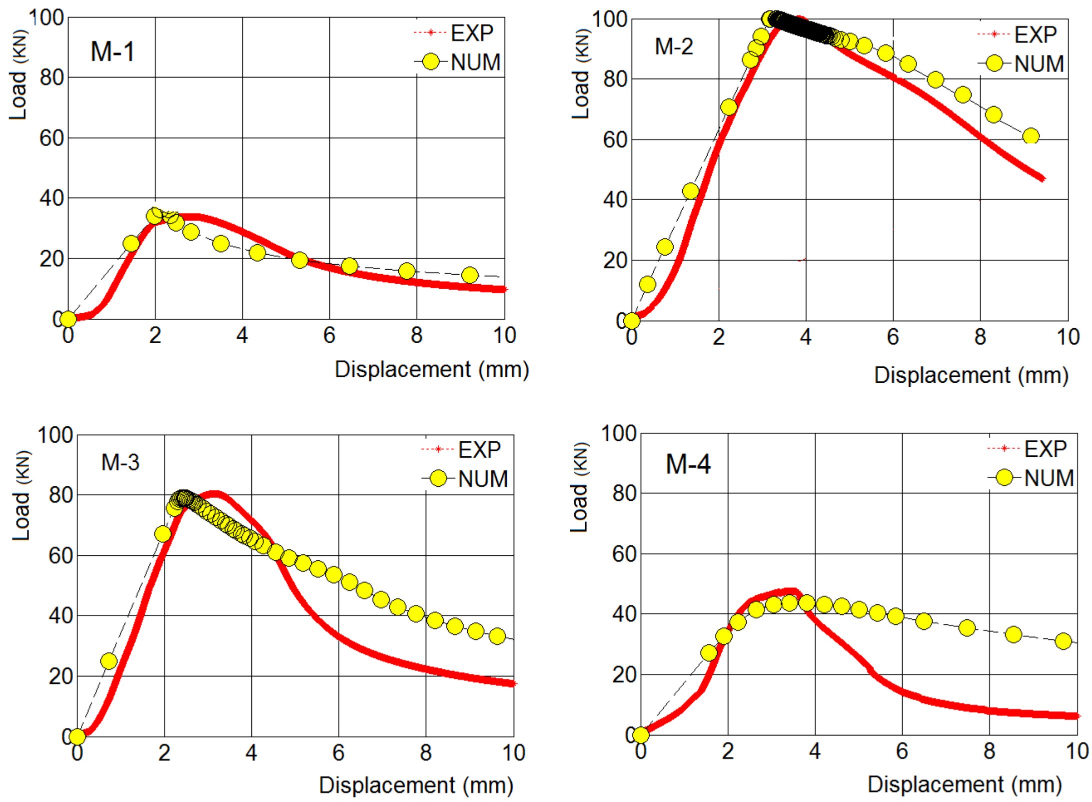

Fig. 16. Comparing the load-displacement diagram obtained from the experiment and numerical modeling.

Fig. 16 compares the load-displacement diagram obtained from the experiment and the numerical modeling.

5. Conclusions

In this study, the methods of retrofitting the members of steel lattice towers by studying 6 different methods of strengthening the compression members have been investigated using experiments and numerical modeling. The results can be summarized as follows:

1) According to the CFD analysis results, the maximum pressure coefficient due to the wind (CP) on the windward surfaces is +1, and the maximum negative pressure coefficient (suction) equals -1.2.
2) Considering that the connections of the steel lattice tower members are typically bolted, connecting the reinforcing members to the primary members using a bolted connection can be suitable. Thus, M3 to M7 models can be appropriate methods for retrofitting the members of this type of structure.
3) In the best case, when the angle is connected to the primary member by welding (M2), the compressive strength of the member is improved by 195%.
4) One of the easy methods of strengthening is the use of clamps, so that angle reinforcement is connected to the primary member using two clamps (M6), In this case, the compressive strength increases by 147%.
5) The M5 model (Three plates connect two Angles) is the closest model to the base model (M2). Therefore, the M5 model, which connects the reinforcing angle to the primary angle using a plate, has only an 11% reduction in resistance compared to the M2 sample, which is connected by welding.

6) According to the load-displacement diagram, the angle connection in a part of the length of the primary member (M4 model) can increase the member's resistance by 38%.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Hossein Sadeghi: performed the modeling and analysis.

Mohammad Khalili Nejad: has conducted the experiments.

Mohsen.Sadeghi: reviewed the manuscript.

References

[1] Baran E, Akis T, Sen G, Draisawi A. Experimental and numerical analysis of a bolted connection in steel transmission towers. J Constr Steel Res 2016;121. https://doi.org/10.1016/j.jcsr.2016.02.009.

[2] Li F, Deng H zhou, Hu X yi. Design resistance of longitudinal gusset-tube K-joints with 1/4 annular plates in transmission towers. Thin-Walled Struct 2019;144. https://doi.org/10.1016/j.tws.2019.106271.

[3] Liang G, Wang L, Liu Y, Geng N. Mechanical behavior of steel transmission tower legs reinforced with innovative clamp under eccentric compression. Eng Struct 2022;258. https://doi.org/10.1016/j.engstruct.2022.114101.

[4] Balagopal R, Ramaswamy A, Palani GS, Prasad Rao N. Simplified bolted connection model for analysis of transmission line towers. Structures 2020;27. https://doi.org/10.1016/j.istruc.2020.08.029.

[5] Tapia-Hernández E, Ibarra-González S, De-León-Escobedo D. Collapse mechanisms of power towers under wind loading. Struct Infrastruct Eng 2017;13. https://doi.org/10.1080/15732479.2016.1190765.

[6] Zou Y, Lei X, Yan L, He X, Nie M, Xie W, et al. Full-scale measurements of wind structure and dynamic behaviour of a transmission tower during a typhoon. Struct Infrastruct Eng 2020;16. https://doi.org/10.1080/15732479.2019.1670679.

[7] Huang MF, Lou W, Yang L, Sun B, Shen G, Tse KT. Experimental and computational simulation for wind effects on the Zhoushan transmission towers. Struct Infrastruct Eng 2012;8. https://doi.org/10.1080/15732479.2010.497540.

[8] Sun L, Trovato M, Stojadinović B. In-situ retrofit strategy for transmission tower structure members using light-weight steel casings. Eng Struct 2020;206. https://doi.org/10.1016/j.engstruct.2020.110171.

[9] Xie Q, Zhang J. Experimental study on failure modes and retrofitting method of latticed transmission tower. Eng Struct 2021;226. https://doi.org/10.1016/j.engstruct.2020.111365.

[10] Moon BW, Park JH, Lee SK, Kim J, Kim T, Min KW. Performance evaluation of a transmission tower by substructure test. J Constr Steel Res 2009;65. https://doi.org/10.1016/j.jcsr.2008.04.003.

[11] Jiang WQ, Wang ZQ, McClure G, Wang GL, Geng JD. Accurate modeling of joint effects in lattice transmission towers. Eng Struct 2011;33. https://doi.org/10.1016/j.engstruct.2011.02.022.

[12] Ma L, Khazaali M, Bocchini P. Component-based fragility analysis of transmission towers subjected to hurricane wind load. Eng Struct 2021;242. https://doi.org/10.1016/j.engstruct.2021.112586.

[13] Ma R, Yu L, Zhang H, Tan L, Kueh ABH, Feng J, et al. Experimental and numerical appraisal of steel joints integrated with single- and double-angles for transmission line towers. Thin-Walled Struct 2021;164. https://doi.org/10.1016/j.tws.2021.107833.

[14] An L, Wu J, Jiang W. Experimental and numerical study of the axial stiffness of bolted joints in steel lattice transmission tower legs. Eng Struct 2019;187. https://doi.org/10.1016/j.engstruct.2019.02.070.

[15] Gan Y de, Deng H zhou, Li C. Simplified joint-slippage model of bolted joint in lattice transmission tower. Structures 2021;32. https://doi.org/10.1016/j.istruc.2021.03.022.

[16] Karimian Sichani M, Keramati A, Behzadinia F. Modification of the euler load for the stiffened compressive members and determination of the optimal stiffening for the maximum buckling load. J Rehabil Civ Eng 2020;8. https://doi.org/10.22075/JRCE.2020.19819.1385.

[17] Vettoretto G, Li Z, Affolter C. Evaluation of the Ultimate Collapse Load of a High-Voltage Transmission Tower under Excessive Wind Loads. Buildings 2023;13. https://doi.org/10.3390/buildings13020513.

[18] Mianroodi M. Experimental and numerical CPFEM-based determination of FLD using biaxial and Nakajima tests: industrial application to deep drawing simulation for FCC and BCC metals 2021.

[19] Bazmara M, Mianroodi M, Silani M. Application of physics-informed neural networks for nonlinear buckling analysis of beams. Acta Mech Sin 2023;39:422438.

[20] Mianroodi M, Touchal S, Altmeyer G. Comparison of Forming Limit Diagrams for FCC and BCC materials using Taylor and Marciniak-Kuczynski models. Int. Conf. Sci. Eng. Technol. ICSET 2019, vol. 7, 2019.