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Enhancing Tower Crane Stability through Mast Bracing and Finite Element Analysis

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***Abstract*—Tower cranes are indispensable assets in modern construction projects, facilitating heavy lifting at towering heights exceeding 100 meters. However, their slender and lightweight design renders them susceptible to buckling failures, particularly in the mast and boom structures, raising concerns about static and dynamic stability. This paper presents a comprehensive finite element analysis methodology to assess buckling behavior in tower cranes, accounting for both structural and mechanical complexities. Through linear buckling analysis, critical buckling modes and load magnitudes are identified, while a comparative assessment is conducted between configurations with and without bracings. The results underscore the mast's compromised stability due to its extended length, leading to diminished stiffness. Conversely, tower cranes equipped with additional bracings demonstrate improved stability and operational safety. Furthermore, numerical simulation is employed to evaluate the efficacy of mast bracing in enhancing tower crane stability. This study emphasizes the pivotal role of mast bracing in augmenting the overall stiffness and stability of tower cranes, particularly in dynamic operating environments. It provides valuable insights into optimizing tower crane design and mitigating risks associated with crane operations in high-rise construction settings.**

***Index Terms*— Tower cranes, Mast bracing, Finite Element Analysis, Stability, Buckling analysis, High-rise construction.**

I. INTRODUCTION

Large-scale construction projects necessitate the use of substantial cranes capable of handling heavy loads and achieving great lifting heights. As aerial operation demands grow and the use of high-strength steel leads to the design of slimmer, lighter frame structures, these slender constructions become susceptible to buckling failures. This is illustrated by tower crane failures resulting from mast buckling, as depicted in Fig. 1. The operational range of a tower crane may vary under different loads, necessitating continuous adjustments of the luffing mechanism to maintain a consistent working range. This highlights the tower crane system as a complex integration of frame structure and mechanisms. Consequently, researching the buckling of tower cranes, with a focus on their mechanical functions, holds significant academic and practical importance.

Existing crane design guidelines offer reference formulas tailored for standard structures subjected to usual loads. These guidelines typically simplify the stability analysis of crane lattice structures by treating them as solid structures, thereby providing a formula for stability assessment. While this traditional approach is effective for straightforward structures like I-section columns, it struggles to accommodate the complexity of intricate frame structures, offering limited insights into their buckling behavior.

Fig. 1. Buckling failure of tower crane

Numerical simulation proves more adept at analyzing the buckling of complex steel constructions, which consist of a vast array of components. The finite element method, in particular, has become a prevalent tool for investigating buckling in various structures, including thin-walled shells, thick plates, circular tubes, columns, and frame structures. However, conducting buckling failure tests on large cranes is prohibitively costly, necessitating multiple experiments to cover different operational scenarios.

Stress testing can enhance the precision of a numerical model for complex structures. Finite element analysis is utilized to explore how various factors affect the local buckling load and ultimate load of crane boom and mast.

This research employs numerical buckling analysis to identify critical buckling modes and the magnitudes of loads at which they occur, alongside comparing configurations with and without bracings. The findings highlight a reduction in stability due to the mast's extended length, which leads to decreased stiffness. In contrast, tower cranes that incorporate additional bracings exhibit enhanced stability and operational safety. The study further utilizes numerical simulations to assess the effectiveness of mast

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bracing in improving the stability of tower cranes. It underscores the crucial importance of mast bracing in increasing the cranes' overall stiffness and stability, especially under dynamic operating conditions. This work offers significant insights for the optimization of tower crane design and for reducing the risks associated with crane operations in the context of high-rise construction projects.

II. Loss of Stability and Equilibrium States

Loss of stability and state of equilibrium are two important concepts in the field of strength-deformation behavior analysis and engineering practice [1]. They refer to the behavior of structures under the influence of external loads and conditions.

1. Loss of Stability: Stability refers to the preservation of a system's equilibrium state under small disturbances. Instability is characterized by the occurrence of large displacements in response to small disturbances. The transition from a stable to an unstable equilibrium state represents a loss of stability. The boundary of this transition is called the critical state, and the corresponding load is termed the critical load.

2. Equilibrium State: The equilibrium state refers to the situation when forces and moments acting on the structure are balanced, and there is no acceleration or movement. This is the ideal state of the structure when it is stable and statically capable of withstanding loads because if it is not in equilibrium, stresses and deformations may form, leading to unexpected failure or overloading of the system.

The concept of stability can be explained through the position of a ball with weight W on a surface of varying shape, as shown in Fig. 2:

Fig. 2. Stable (1) and unstable (2) equilibrium

Position 1 is stable, as any small change returns the ball to its original position. Position 2 is unstable, as any change in position moves the ball away from its original location. This latter behavior is manifested as a loss of stability in mechanical thin-walled structures under compressive loads.

Loss of stability (buckling) is a mechanical phenomenon that occurs suddenly in structural elements, most often when they are subjected to compressive loads. In reality, structural elements often have imperfections or are subjected to uneven loading, which can affect their behavior during loss of stability.

Post-buckling occurs when the deformed shape becomes unstable, and the element undergoes additional deformations or even collapses with a relatively small increase in the load. The subsequent unstable behavior is often associated with local loss of stability, material plasticity, or other forms of structural instability.

To achieve stability and equilibrium of structures, various design techniques, materials, shapes, and analyses based on the theory of mechanics and structural analysis are employed. This ensures that structures are safe, stable, and comply with specified specifications and standards [1], [2].

The analysis of the behavior of the structure after the loss of stability can be complex and requires nonlinear study with the Finite Element Method (FEM) or other numerical methods. These methods take into account geometric nonlinearity, material nonlinearity, and contact interactions that may occur during the deformation following the loss of stability [3].

A. Analysis of the Most Common Types of Loaded Structures at Risk of Buckling

Considering a long bar (Fig. 3) subjected to both centric tension and centric compression, in the first case, the bar remains straight until it fails, while in the second case, upon reaching a certain force P, maintaining a straight equilibrium form becomes impossible – at this force, the bar suddenly bends. We say that the bar loses stability. The force P that causes the loss of stability is called the critical force, and the phenomenon of bar bending is referred to as buckling.

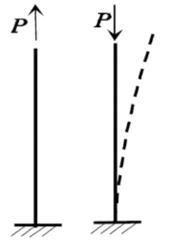

Fig. 3. Bar under axial tension and compression load

The general definition states: If a system returns to its original equilibrium state after being displaced from it, that equilibrium state is stable; if the system does not return to its original state, it is unstable.

A tendency towards loss of stability is exhibited by all thin-walled structures primarily under compression, but loss of stability can also occur due to bending, torsion, or thermal gradient [4]-[6]. Fig. 4 shows four cases of structural buckling (dashed lines indicate the new positions of the systems after buckling):

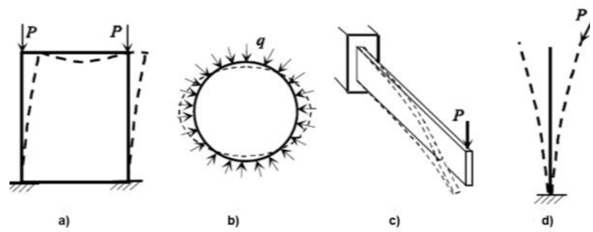

Fig. 4. Buckling examples

a) A planar frame under the action of compressive forces;

b) A circular frame (or cylindrical shell) under the action of an external pressure distributed load;

c) A thin-walled beam bending in the direction of its higher rigidity;

d) A bar subjected to pressure from a following force that acts tangentially to the deformed axis of the bar at all times;

In the last case, it turns out that at a certain value of the force P, the bar begins to perform oscillatory movements [7].

The critical load is denoted by P_{cr}, q_{cr} - this is the magnitude of the external load at which the structure loses stability. Clearly, a state of stability loss is unacceptable for any structure. For this purpose, a safety factor (n_{bck}) against buckling is introduced, with the help of which the magnitude of the allowable load [P], [q] is determined:

$$[P] \leq \frac{P_{cr}}{n_{bck}}, [q] \leq \frac{q_{cr}}{n_{bck}}$$

Here P_{cr}, q_{cr} are calculated, and n_{bck} is a safety factor that is chosen to be greater than 1 ($n_{bck}>1$). When a structure loses stability, three possible behaviors can occur:

1) The structure collapses. This scenario is the most unfavorable. It occurs if, as a result of the loss of stability of a given element, the structure becomes kinematically variable.

2) The structure incurs plastic deformations but continues to serve its purpose. This scenario is reached when the load on the deformed element is taken up by other elements of the structure.

3) The structure begins to perform oscillatory movements. This scenario is observed under the action of the following force.

The critical point, after which the displacements of the element become very large, is called the bifurcation point of the system. Upon buckling, the structural element may deform perpendicularly to the axis with the maximum moment of inertia in two directions. This phenomenon is called bifurcation, illustrated in Fig. 5 [1]

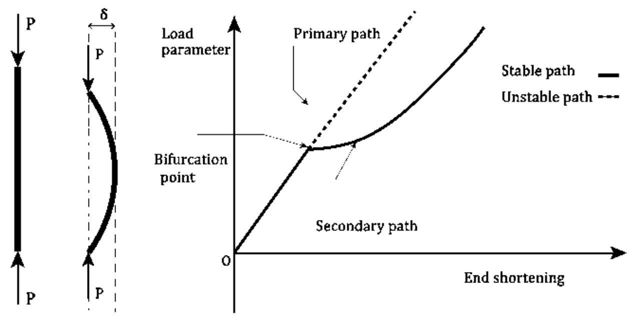

Fig. 5. Stable and unstable postbuckling path of bar under axial force

B. Buckling of Bars, Euler's Column Equation

The classical theory, developed by Euler in the 18th century, provides a fundamental understanding of stability loss in idealized structures [8]. For a perfectly straight, axially loaded, and supported bar with a constant cross-section, symmetric at least along one of the principal axes, initially in an upright position, the first two forms of stability loss are shown in Fig. 6

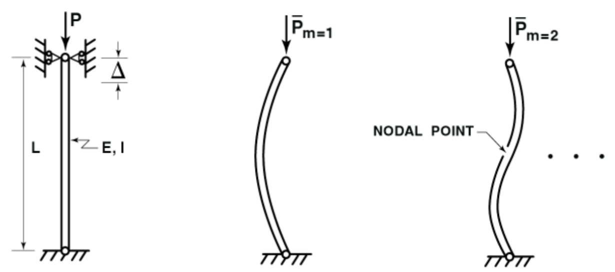

Fig. 6. Axially loaded bar and first two buckling modes

These forms depend on the parameter m from Euler's equation for stability loss:

$$\bar{P} = P_E = P_{cr} = m^2\pi^2\frac{EI}{L^2}, m = 1,2,3, \ldots$$

where $P = P_E = P_{CR}$ is the critical load, m is the number of half-sine waves in the buckling shape, E is Young's modulus of the material of the bar, I is the moment of inertia of the cross-section against bending, and L is the length of the bar. If m=1, the first buckling mode is half a sine wave, and for m=2, the second mode corresponds to 2 halves of sine waves. The critical load depends on several factors, including the properties of the element's material, dimensions, boundary conditions, and geometric imperfections. The nodal point, indicated in Fig. 5, does not move axially during stability loss. If somehow this point is supported, the bar will be protected from the first mode and will only lose stability at P_m=2; at Pm=1, the support prevents movement of the key point. Fig. 7 shows several common cases of bar support and the significance of the coefficient m [7]:

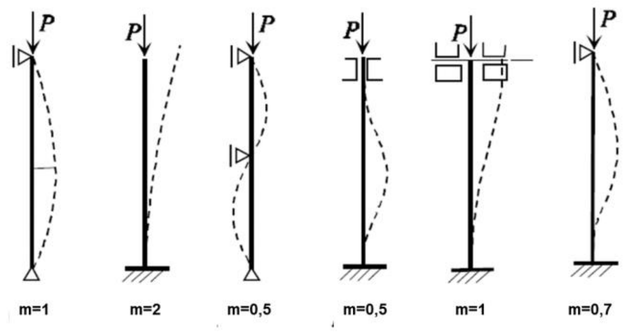

Fig. 7. Types of bar fixation and corresponding values of m

Euler's solution has identified weaknesses, which are due to the fact that in deriving the differential equation for stability, Euler used the simplified differential equation of the elastic curve, which is only valid for small displacements.

$$EIW'' + PW = 0$$

M(x)=PW is the bending moment at any cross-section, I_{min} is the principal moment of inertia (EI=const), and EIW″=-M(x) is the reaction force in the differential equation of the elastic curve.

In reality, after the initial curvature of the bar, its deformations continue to grow and can only be determined after using the full differential equation of the elastic curve. Then, the differential equation of the bar's equilibrium takes the form:

$$EI\frac{W''}{(1+W'^2)^{\frac{3}{2}}} + PW = 0$$

This differential equation is much more difficult to solve. However, at the initial moment of the bar's deformation (when displacements are small), both equations yield the same solution. Therefore, Euler's solution, which provides the value of the critical force at the start of the bar's deformation, is entirely acceptable [9].

One of the common design challenges engineers face is finding the form of stability loss for bars with cross-sections, as shown in Fig. 8 [1].

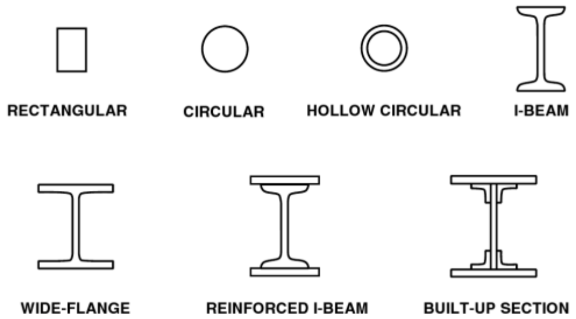

Fig. 8. Typical bar and column cross-sectional shapes

There are various ways to achieve an effective cross-section with a large moment of inertia to protect the bar from buckling. Here, Euler's rule for critical force applies again, which is practically the maximum load a bar can sustain. At slightly higher loads, the bar remains stable but at the expense of axial shortening, and this deformation is not acceptable in most cases [6].

III. Specifics of Finite Element Buckling Analysis

One of the main approaches of computer engineering is the design and evaluation of mechanical details and systems using the Finite Element Method (FEM). Since analytical solutions exist only for simplified cases, real and complex systems are investigated with a substitute finite element model that corresponds to reality and for which a numerical solution exists. The efficiency, low costs, and good applicability of the method make it an indispensable tool and complement to experimental research today. With its help, the need for expensive prototypes and experimental setups when introducing a new product is reduced, saving time and materials and cutting production costs [10]. The Finite Element Method originated in the mid-1950s. The core idea of the method is the split of the continuous medium (continuum) into small elements of specific shape and size (Fig. 9) (hence the method's name), for which the solution to the respective problem is sought. Once the solution for one element is known, the solution for the entire domain can be found [3].

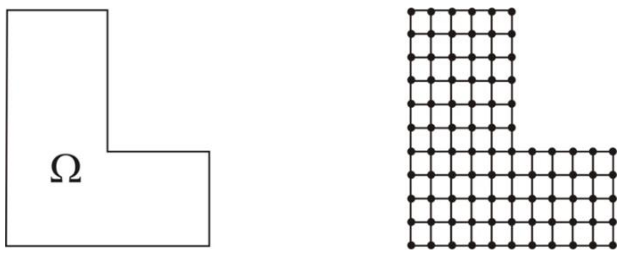

Fig. 9. Finite element discretization

Given a linear material, the following equation applies to each element:

$$F_i = k_{ij} u_j$$

where F_i is the applied force, and u_j is the displacement. k_{ij} is called the stiffness coefficient, and the entire stiffness matrix for the continuum is found through superposition. If the loads are known and the stiffness matrix is inverted, the displacements are obtained, and from there, stresses and deformation of the body can be determined using Hooke's law.

Most finite element software supports the simulation of buckling behavior. Typically, the problem of stability loss is considered by extracting the eigenvalues from the global system stiffness matrix. This method is known as linear buckling analysis. It is attractive from the perspective of short computation time. Compared with the general incremental analysis, which calculates the entire nonlinear behavior of the structural system, it deals only with one or two points of the equilibrium states. Using the method of linear buckling analysis to investigate bifurcation instability yields relatively accurate results in each of the software packages. However, for instability with a limit point (structural collapse), a deviation might occur.

In Abaqus, buckling analysis is conducted using the **buckling* analysis procedure. Initially, the model of the structure is defined with the necessary geometric and material properties, as well as the applied loads and boundary conditions are set. The analysis is executed within the framework of a static analysis but with specific buckling parameters that allow different forms of structural deformation. The mathematical formulations for calculating the critical load, implemented in Abaqus are defined as follows:

- $[K_0]$ is the linear elastic stiffness matrix, whose elements are independent of the structural state.
- $[{}_tK_\sigma]$ is the initial stress matrix, which depends on time t.

The sum of these two matrices is known as the tangent stiffness matrix [11].
${}_0T$ is the equilibrium state without external influences.
${}_tT$ is an intermediate equilibrium state before reaching stability loss.
Δt is the step change of the equilibrium state.
${}_{cr}T$ is the critical equilibrium state at the point of stability loss.
{P baseline} is the external force that leads to state ${}_tT$, $\{P_{characteristic}\}$ leading to ${}_{t+\Delta t}T$ and $\{P_{cr}\}$ to ${}_{cr}T$, and [K] is the structure's stiffness for a given load P and the corresponding displacement. This leads to the two types of formulations [12]:

Classical Formulation:

$$det\left(\left[K_{0,0T}\right] + \lambda\left[K_{\sigma,tT}\right]\right) = 0 \Rightarrow \{P_{cr}\} = \lambda\{P_{baseline}\}$$

Perturbation Formulation:

$$\boldsymbol{det([K_{baseline}] + \lambda[K_{characteristic}] - [K_{baseline}]) = 0}$$

$$\Rightarrow \{P_{cr}\} = \{P_{baseline}\} + \lambda(\{P_{characteristic}\} - \{P_{baseline}\})$$

There is an option to choose between the two methods. Comparison with analytical results shows that the classical method gives small deviations when there is plastic deformation of the structure but no failure, while the perturbation formulation yields better results in the event of material failure. Let's look more closely at the linear buckling analysis with calculation of the eigenmode in Abaqus for this class of problems [13]: This uses an estimate of the critical (bifurcation) load on "ideally rigid" structures and is executed as a fully linear step. It is typically used for estimating the critical loads of rigid structures. The eigenvalue analysis provides a reliable estimate of the load only if the assumptions of small geometric changes and linear elastic response of the material before stability loss are realistic for the modeled structure and if the deformation is not sensitive to imperfections.

Other factors influencing the results of buckling analysis include the type and quality of the mesh in the model, as well as the material data. Elements must meet the quality criteria defined in the programs and be sufficient in number to accurately represent the real geometry. Typically, problematic elements are logged during the calculations by the solver, and the simulation may even stop if there are too many or if they are excessively deformed. For material data, the accuracy with which they represent the elastic-plastic behavior of the actual material matters, including whether they are simplified and to what extent.

A. Validation of Simulation Result Accuracy

To validate the accuracy of finite element calculations, let's consider one of Euler's examples of a compressed elastic plate, with fixed translation at one end and a longitudinally movable joint at the other:

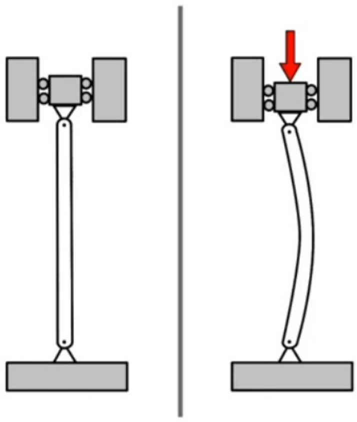

Fig. 10. Validation model

A plate with the following specifications: 300 mm in length, 26 mm in width, and 0.8 mm in thickness. The material is linear-elastic steel with a Young's modulus of E=210,000N/mm. In Abaqus, 2D elements with reduced integration were utilized. The plate is subjected to a uniform load of 1 N/mm, resulting in a total load on the upper edge of P=1N/mm×26mm=26N. A linear buckling analysis was conducted using the Riks algorithm (STATIC, RIKS). The outcome of this analysis is illustrated in Fig. 11.
From the simulation results, the critical load calculated by the simulation is given by:

$$P_{cr,sim} = P.EigenValue = 26.0{,}98379 = 25{,}57853\ N$$

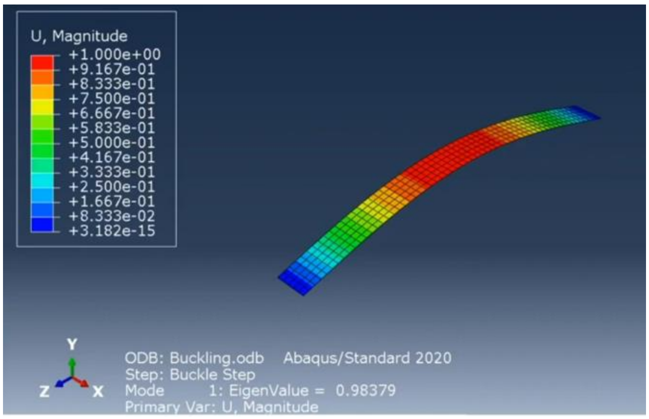

Fig. 11. Displacements U and first eigenvalue

Euler's solution for this case involves solving the differential equation for buckling, where:

$$M(x) = Pw,\ w'' = -\frac{P}{EI}w,\ w'' + k^2 w = 0$$

with the general solution:

$$w = C_1 coskx + C_2 sinkx$$

Given the boundary conditions at x=0,w=0, we get $C1$=0; at x=l, w=0, it leads to $C_2\sin(kl)=0$ which implies $C_2=0\sin(kl)=0 > kl=\pi,\ 2\pi$. The moment of inertia I for the plate is calculated as:

$$I = \frac{1}{12}bh^3 = \frac{1}{12}.26.0{,}8^3 = 1{,}1093mm^4$$

For the first mode of buckling, the critical load is:

$$P_{cr} = \frac{\pi^2}{l^2}EI = \frac{\pi^2}{300^2}210000.1{,}1093 = 25{,}546\ N$$

Therefore, the deviation of the simulation result $P_{cr,sim}$ from the analytical solution P_{cr} is 0.13%. This small deviation indicates a high degree of accuracy in the simulation results, validating the finite element model and simulation approach used.

IV. NUMERICAL MODELING

A. Finite Element Model

In the study, a tower crane with a height of 100 meters and a maximum lifting capacity of 80 tons (Q_1) is examined. The model simplifies the crane's boom by not modeling it explicitly; instead, its weight (Q_2) is included in the total load on the tower Q, along with the counterweight (Q_3). The material is linear steel with a Young's modulus (E) of 210,000 N/mm² and a Poisson's ratio (ν) of 0.3. The truss structure is modeled with beam elements that have a circular profile, providing a simplified yet effective representation of the crane's structure (Fig.12).

The crane is fixed to the base to simulate real-world operational conditions, ensuring the structure's stability for the analysis. A linear buckling analysis is employed to calculate the first eigenmode and frequency, along with the corresponding deformations. This analysis is crucial for identifying the load at which the structure is likely to lose stability, signifying the critical buckling load. By focusing on the first eigenmode, the study aims to understand the primary way in which the crane might buckle under load.

This approach allows for the evaluation of the structural integrity of the crane, ensuring that it can safely carry the designated loads without risk of buckling. Understanding the deformation patterns and the critical load capacity is essential for designing safe and efficient tower cranes. The use of linear buckling analysis provides valuable insights into the behavior of the crane under load, guiding engineering decisions to enhance safety and performance. Through this simplified model, the crane's stability is assessed, then design parameters can be refined, and necessary reinforcements implemented to mitigate the risk of structural failure.

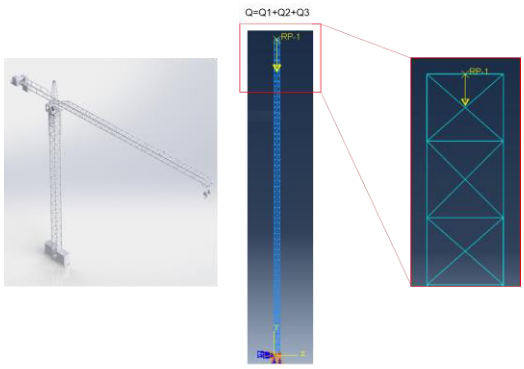

Fig. 12. Finite element model of the tower crane

The results in Fig.13 indicate an expected deformation and an eigenvalue/safety coefficient of 0.79.

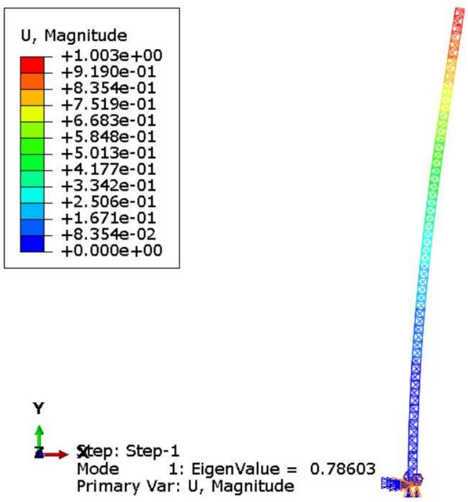

Fig. 13. Buckling critical load factor and deformation

Since this value is less than 1, buckling occurs, implying that the crane will lose stability before reaching the extreme load condition. This outcome underscores the significance of conducting a detailed structural analysis during the design phase of tower cranes. A safety coefficient of less than 1 reveals that under the specified load conditions, the crane is at risk of buckling, which could lead to catastrophic failure if not addressed. The analysis serves as a critical alert for engineers to either redesign the structure to enhance its load-bearing capacity, incorporate additional support mechanisms, or reduce the maximum allowable load to ensure that the crane operates safely within its structural limits.

Such findings are instrumental in guiding the development of more robust and secure crane designs, emphasizing the need for thorough testing and validation of structural integrity under various loading scenarios. The buckling analysis not only helps in identifying potential failure modes but also plays a crucial role in the implementation of preventive measures to safeguard against structural collapse, ensuring the safety and reliability of tower crane operations

B. Influence of Mast Bracing

In the next step, bracing has been added to the crane model, which serves to stiffen and strengthen the mast against various critical loads. The other parameters remain unchanged. This addition involves integrating bracing elements into the existing finite element model of the tower crane. The primary goal of these elements is to enhance the structural rigidity and stability of the mast, effectively increasing its resistance to buckling under compressive forces and improving its overall response to lateral loads such as wind or dynamic loads associated with crane operations. The bracing is placed in the middle of the mast structure at 50m height, connecting different sections of the mast. The configuration, including the orientation and spacing of the bracing, is designed to optimize the distribution of forces throughout the crane structure. The material properties of the bracing match those of the mast, typically steel, to ensure compatibility in stress responses. The geometric properties, including the cross-sectional area and length of each bracing element, are defined based on structural requirements and design standards. The primary parameters remain unchanged. With the integration of bracing, additional simulation runs are performed to evaluate the impact on the crane's structural performance. This includes assessing changes in the critical load factors, displacement under operational loads, and the crane's susceptibility to buckling. The results are shown in Fig. 14. The eigenvalue has increased to 3.59, indicating that the crane has been effectively reinforced and the risk of buckling has been eliminated.

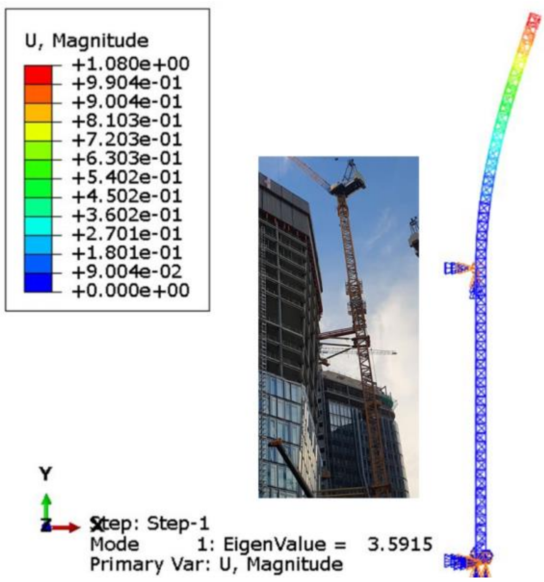

Fig. 14. Critical load factor and deformation with mast bracing

V. CONCLUSION

This paper outlines a detailed method using finite element analysis to study how tower cranes might buckle under pressure, taking into account the complex details of their structure and mechanics. By performing linear buckling analysis, it identifies the most critical points where buckling could occur and how much load can cause this. It also compares crane designs with and without added supports (bracings). The findings highlight that the long mast of the crane makes it less stiff and stable. However, adding bracings to tower cranes makes them more stable and safer to use. The safety factor increases from 0.78 to 3.59. Additionally, this paper uses simulations to see how well bracings work to make tower cranes more stable. It points out how crucial bracings are for making the cranes sturdier and more reliable, especially when they are used in situations where they move a lot. This research offers important advice for making tower cranes better and safer for building tall structures

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