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RESEARCH ARTICLE

Performance and safety assessment of steel structures in substations using nonlinear time-history analysis

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ABSTRACT

Electrical substations control voltage and the flow of electric energy, assuring optimal electricity transmission from generation plants to users. A detailed performance evaluation of the substation's structures is crucial to deciding whether to demolish or repair. This study analyzed a 200 KV substation's steel structure in China to find an efficient assessment strategy. Structural data and dimensions have been carried out through a holistic site inspection. Different laboratory tests have been conducted to evaluate the material's strength. The finite element method (FEM) has been utilized to develop the structural model, and nonlinear static and time-history analysis has been done with STAAD.Pro-2023. To assess the structural safety of the steel structure, necessary factors such as time-frequency, mode shape, deflections, and strength capacity ratios were studied. Structural data was found from structural analysis, and the Structure's present condition was compared with its initial conditions and allowable limits. The study's findings show a 15% reduction in natural frequencies and extended structural periods, indicating material degradation and potential reductions in dynamic resilience. The strength capacity ratio of the steel structure members was lower than the initial condition.

Keywords: Steel structure; Substation; Time-history analysis; Deflection; Performance evaluation

1. Introduction

In China, the proportion of infrastructure over 50 years old is increasing. According to Chinese authorities, the proportion of these kinds of constructions will rise to 60% within the next 20 years. Therefore, it is essential to provide effective upkeep and evaluation for those buildings[1]. Many interrelated types of electrical accessories, mechanisms, and supporting structures comprise a substation; examples include power/modern convertors, independent buttons, circuit rollers, modifiers, supporting paddings, and portal surrounds. Cui et al. proposed an evaluation method for steel structures in substations under seismic events in strong earthquake-prone areas. They proposed a method for post-earthquake rapid assessment of steel structures in substation[2]. A detailed seismic risk analysis of an electrical substation was conducted by Baghmisheh et al., who proposed a reliability-based method to assess seismic vulnerability while considering

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uncertainties[3]. Dynamic analysis and time-history analysis have been conducted to assess the seismic risk analysis of many studies[4]. The seismic performance of various single and linked electrical equipment components has received much attention[5]. Numerous studies have been conducted on residential and industrial structure assessment and retrofitting. However, substation steel structures are still lacking[6,7]. Cold-formed steel (CFS) construction use has grown dramatically in residential and industrial sectors recently. Its many advantages over traditional methods—such as its improved quality, ease of manufacturing, and relatively light weight—have made it a viable replacement[8]. Most electric power substations (EPS) are constructed utilizing hot-rolled steel angle truss constructions, primarily outside communities[9]. Due to environmental effects, these steel structures are often affected by corrosion; corrosion can cause resource waste and economic losses and significantly impact the performance and safety of steel structures[10]. In the past few decades, a great deal of analytical and experimental research has been done to maximize the capacity of cold-formed steel sections in CFS configurations. A few experimental tests using different configurations on full-sized samples were conducted by researchers[11] to determine the impact of mechanical clinching in steel trusses. Zeynalian[12] also carried out an investigative inspection of cold-formed steel truss associates to control the samples' ultimate load capacity and the connection failure machinery; his study looks into the primary causes of the CFS truss connections' ductile response and ways to make adjustments so that the connections respond plastically with a noticeable drift and no chance of brittle failure. Chang and Wu[13] evaluated the electrical grid's vulnerability to cascade failures, and they stated that due to strong earthquakes, cascading failures could occur. They looked at its resilience to ground motion during earthquakes. The functional evaluation standard and the quick response plan under the cascading impact are crucial for assessing substation resilience. Two main perspectives were used in investigating seismic retrofitting and power system resilience optimization: technological and operational. While equipment reinforcement and situational awareness monitoring are examples of expertise, emergency repair plans and resource transportation strategies are related to measures. Increasing redundancy and adding more parts are critical steps, even if they have nothing to do with upgrading, maintaining, or fixing a component. Nonetheless, many studies have been conducted on strengthening power systems' resistance to catastrophic events[14]. Song et al. researched the evaluation of structural resilience, provided a set of rules for evaluating the amount of resilience, and developed five categories for the substation's resilience[15]. They also proposed a methodology that takes seismic intensity, building weighting coefficients, and high-voltage electrical equipment into consideration when determining the resilience index of the buildings. In addition to the resilience assessment of the substation, one should consider the financial value of the seismic approach. Since then, there has been a lot of interest in resistance-based design methods for substation structures. Based on the post-earthquake retrieval prototype of the power structure built by Cagnan and Davidson, the recovery scenario and skeleton curves for the Los Angeles power system were developed[16]. They proposed a new simulation model that can use strong earthquake-prone areas to get the performance of substation structures. Wang et al. researched substation secondary equipment; according to his research, Relay protection devices can have their performance status assessed more accurately if the intrinsic influence of subjective and objective evaluation criteria is taken into account using the IAHP-EW approach[17]. According to the research of Liu et al. based on vibration response and isolation of substation structure, vertical vibration predominates in the substation construction when subway loads are excited, and that vibration response progressively rises with floor level[18]. Zhuang and Xie proposed a method to discretize the continuous rehabilitation process and linearize the seismic resilience evaluation process. The case study shows that the MILP rehabilitation strategy can find the globally optimal rehabilitation sequences in most simulated scenarios, which increases the restorative capacity[19]. Feasibility evaluation of Copula theory for substation equipment has been done by Wen et al., who stated that the widely used Gaussian Copula exhibits evident limitations. At the same time, the Archimedean family Copula is more suitable for substation equipment assessment. Traditional methods that do not consider multiple failure modes or neglect correlation between different modes yield significantly lower seismic vulnerability than the Copula-based method that considers correlations[20]. Soleymani and Saffari used nonlinear cyclic and time history analysis to inspect hybrid seismic resisting formation. They demonstrate that the hybrid strong-back-shear link (SB-SL) system showed uniform displacements, decreasing the soft-story issue more than the traditional bracing system[21]. While many studies have been conducted to assess the seismic performance of steel structures in substations, the majority of these studies rely on software simulation and laboratory experiments that take into account the mechanical properties of corroded steel, including its strength, elastic modulus, ductility, stress-strain relationship, etc. There is a dearth of research on these sites that use real-site architecture. Considering the advantages of CFS structures, the current study aims to evaluate the lateral enactment of the CFS truss system through an accurate site survey and the current steel structures in the substation, including assessing their seismic reaction alteration effects. In this study, several site inspections and some non-destructive testing have been carried out. This work examines the nonlinear dynamic response analysis of substations with structure-equipment interaction. This research has shown variations in mode shape and time history analysis.

2. Significance of the research

Over 50% of substation structures in China are expected to surpass 50 years by the next decade. However, there is enough research about the assessment and rehabilitation of building structures; there is a lack of sufficient safety assessment and retrofitting methods for these structures. Steel structures in substations are generally subjected to extreme environmental conditions and require detailed evaluation to determine their integrity. While existing research focused on the seismic assessments of substations and the resilience of structural members under dynamic loads, most research relies on simulations or laboratory experiments. This study offers a significant contribution by assessing an on-site 200 kV substation's steel structure through a comprehensive method. This study consists of several practical stages such as field inspection, laboratory testing, advanced FEM method, and time-history analysis to evaluate the dynamic behavior of the Structure under wind and seismic loads. The primary novelty of this research is its focus on field investigation of an actual project, non-destructive test of the structural members, and dynamic analysis of the Structure. This study provides data about the degradation procedure of structural performance with age. In this study, the widely known structural analysis software STAAD.Pro has been used to provide guidelines to practicing structural engineers to enhance the existing methods of structural assessments. This study emphasizes the importance of degradation in natural frequencies, strength capacity ratio of steel members, and dynamic resilience due to material aging, providing valuable insights for future structural health monitoring and retrofitting strategies for substation structures.

3. Methodology

For this study, a substation structure in a coastal region in China has been used. The site has been inspected to obtain precise site data. Owing to safety concerns, entry inside the site was prohibited. A few skilled substation workers who used vibration tools assisted us in carrying specific data, including vibration measurement data. An external visual inspection of the substation has been conducted. **Figure 1** displays the research process of this study.

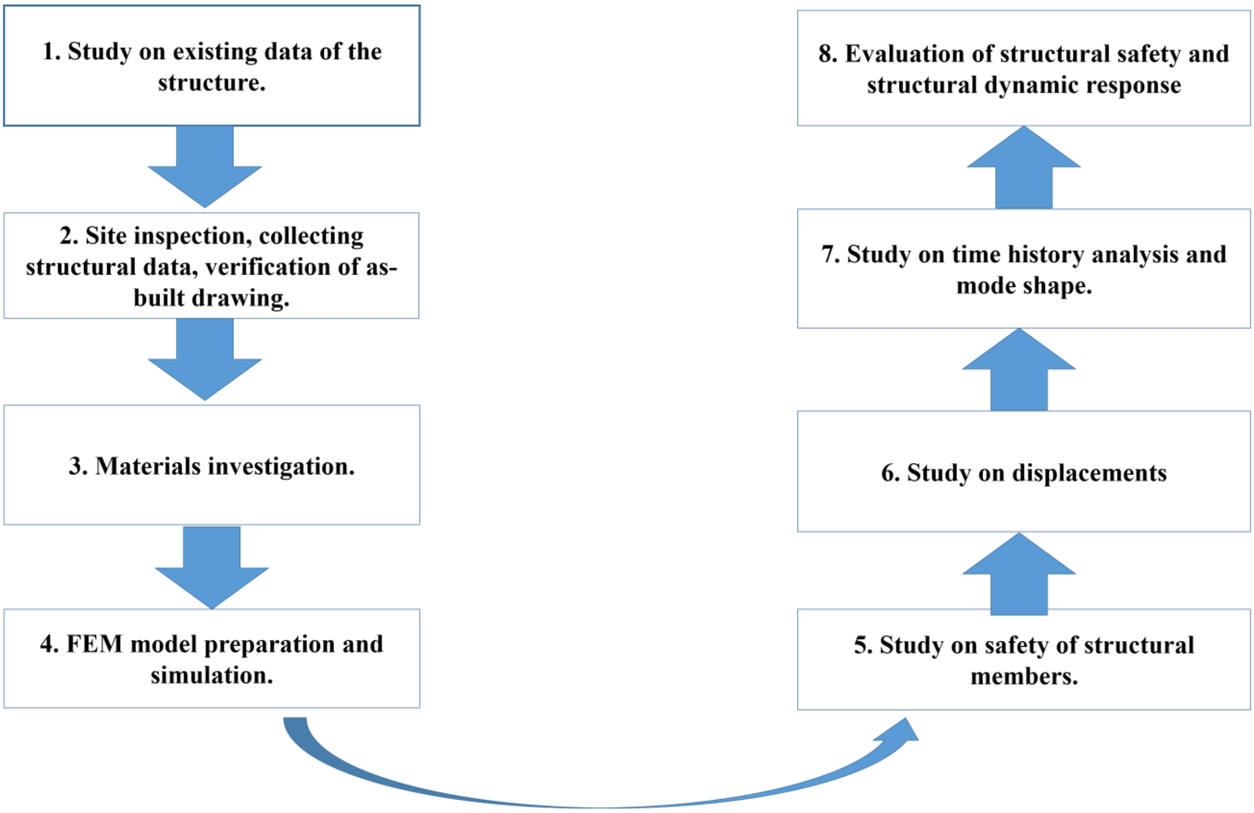

Figure 1. Flow chart of the research process.

The substation authority's earlier plans and drawings were the basis of all structural documents. **Figure 2** demonstrates the photo of the site inspection. Structural analysis software STAAD.Pro is a widely known popular software used for several research[22,23]. In this study, STAAD.Pro-2023 has been utilized to develop a FEM model as a three-dimensional structure and analyze the Structure.

Figure 2. Photo of the site.

This study involves the modeling and analysis of steel truss structures using STAAD.Pro, after gathering structural data based on field inspection, alongside material strength tests, a comprehensive structural model was developed and assessed. Based on field investigation, the structural members are designed as angle sections and pipe columns. To optimize any structural member section, all wind load computations were repeated simultaneously for analysis and evaluation. Using the conventional analysis method, the stabilities of structural members cannot be evaluated directly as these issues are nonlinear[24]. At the cross-sectional, member, and frame levels, nonlinear behaviors are classified as materially and geometrically nonlinear. This research offers a simple, effective, accurate method for nonlinear time-history earthquake analysis of steel structures. The Structure has been analyzed using the ASCE load combination for the substation, considering all forms of gravity, equipment, and seismic loads. Data on acceleration, time-frequency, deflection, and strength capacity ratio were gathered from the software and compared with the allowable limit. The building is made up of eight 26-meter-long spans. **Figure 3** shows the 3D structural model collected from the software.

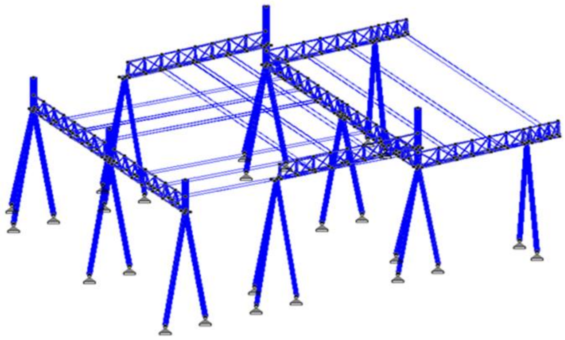

Figure 3. 3D model of the structure.

According to the field investigation, the structural system is a steel lattice frame structure. A 3D space frame model was developed using STAAD.Pro. Bolted, welded, pinned, and gusset connections have been found in the field survey. Fixed moment, pinned, bolted connections have been considered in the FEM model. Base plate and anchor bolt connections have been found at the base of the steel column, and fixed base connections have been considered in the FEM model. A pipe column and angle truss system with a cantilever truss comprise the main structural Structure. The structural height is 21.5 meters above the earth. Steel has been reported to have a tensile strength of 36 ksi at the initial stages, and 32 ksi was found in the laboratory test for its current condition. For the Structure, nonlinear static, dynamic, and time history evaluations have been completed.

3.1. Loading criteria

The Structure's self-weight, equipment load, weir tension load, connection load on the strain bus system, seismic load, extreme wind load, ice load and short circuit loads have been considered during the Structure's analysis[25]. The seismic strategy force, FE, can be computed using equation 1 by applying an equivalent lateral force approach to the computation of structure earthquake loads[25].

$$F_E = \left(\frac{S_a}{R}\right) W (I_{FE})(I_{MV}) \tag{1}$$

Where W = dead load (which includes entirely equipment that is strictly devoted and 50% of the weight of any involved cable),

Sa = strategy supernatural response acceleration.

I_{MV} = 1.0 for dominant single-mode behavior or 1.5 when considering multiple vibration modes.

R = structure-response modification factor.

I_{FE} = importance factor for earthquake loads.

F_E = lateral energy practical at the center of the severity of the Structure or constituent.

The maximum loading is determined by how wind loads are applied to substation equipment, structures, and conductors (bus and wire). The following formula 2 can be used to calculate the wind force[20]:

$$F = QK_Z V^2 I_{FW} G_{RF} C_f A \quad (2)$$

V = basic wind rapidity and the 3-s gust wind rapidity (miles per hour, meters per second).

I_{FW} = importance factor.

G_{RF} = gust response factor (for the Structure and wire).

C_f = force coefficient.

A = predictable wind surface zone is usually used for the wind route (ft2, m2).

Q = air mass factor, defaulting value = 0.00256 (0.613 SI).

According to ASCE[26] rules, load combinations have been applied as shown in **Table 1**

Table 1. Design consideration for ultimate strength and load features.

Load Cases	Load Factors and Combinations
Case 1	1.1 D + 1.2 WI + 0.75 SC + 1.1 T_W
Case 2	1.1 D + 1.2 IW_{IF} + 1.2 $W_I I_{FI}$ + 0.75 SC + 1.1 T_W
Case 3	1.1 D + 1.0 SC + 1.1 T_W
Case 4	1.1 D + 1.25 E (or E_{FS})I_{FE} + 0.75 SC + 1.1 T_W

Where,

D = structure's dead load.

W = stirring wind load.

W_I = wind load in grouping with ice.

E_{FS} = earthquake load.

T_w = earthquake load retorts from the first upkeep levied.

SC = short-circuit load.

$I_{F,}$ I_{FE}= Important Factor

3.2. Consideration of deflection

Deflection is the amount of bending or deformation a structural member undergoes in reaction to an external load. Deflection is a fundamental concept in structural design since too much of it can lead to a structure collapsing or sustaining damage, altering how the building functions and appears. The area between associates and vertical supporting members, or, in the case of cantilever supporters, the space from the topic of exploration to the standing secondary member, is the span of a horizontal participant for calculating maximum deflections[27,28]. Maximum deflections are determined by taking a standing member's upright distance, or span, from the foundation support to the Structure's plug of examination. **Table 2** shows the acceptance criteria for deflection.

Table 2. Deflection of the acceptable limit of the structure.

Member Type	Direction of Deflection	Permissible Limit
Horizontal	Vertical	L/200
Vertical	Horizontal	L/100

3.3. Consideration of time-history analysis, frequencies and mode shape

One of the most prominent methods to evaluate the performance of a structure throughout an earthquake is a nonlinear Time History analysis[29]. The method considers the elastoplastic deformation of the structural element. It is founded on the mathematical incorporation of motion discrepancy calculations[30]. Engineers can ensure a structure's durability and safety by evaluating its performance under intense loading situations thanks to time history. The time history technique provides all potential forces that may be generated and the resulting structure displacement during the whole ground motion duration at equal intervals, usually 0.05 to 0.1 seconds. Time-history investigation is the behavioral analysis of a structure under prior earthquake or wind acceleration data. A component's mode shape shows the distortion it experiences when vibrating at its inherent frequency. A component deforms by its mode shape when it vibrates at its intrinsic frequency. Variations in model forms have been noted in this study among different modes. Regardless of the excitation forces' frequency content, a precise frequency corresponds to each mode shape of the excited Structure.

4. Result and discussion

Nonlinear static and nonlinear dynamic analyses have evaluated the Structure's safety performance, considering time history analysis and mode shape changes. The LFRD design and analysis method has been used to calculate each structural member's strength capacity. ACD analysis methods have been used to evaluate the Structure's serviceability.

4.1. Strength capacity evaluation of all structural members

Demand Capacity Ratio (DCR) is used to analyze which structural element has exceeded its load-carrying capacity and potentially led to tolerant failure[27]. Below, equation 3 is used to determine the DCR values based on the linear elastic static analysis.

$$DCR = M_{max} / M_p \tag{3}$$

Here, M_{max} = moment. Demand was intended using linear variable inert analysis from STAAD.Pro.

M_p = eventual moment ability (malleable moment) calculated for each structural member.

The Structure's acceptance criteria are based on the demand capacity ratio limits. If the SCR is below 1.00, it has been considered safe; if it's greater than 1.00, it has been considered an overstressed structural member, which can be expressed by equations 4 and 5.

$$Developed\ DCR < 1.00 = \ Safe \tag{4}$$

$$Developed\ DCR > 1.00 = \ Unsafe \tag{5}$$

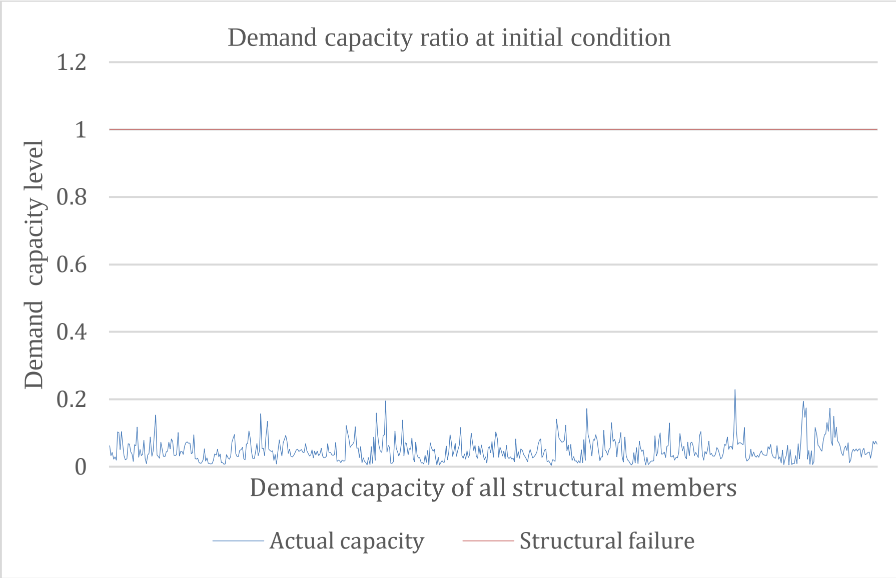

Figure 4. Demand capacity ratio of structural members at initial condition.

This study's demand capacity ratio for all structural members was less than 1.00, as shown in **Figures 4** and **5** for the Structure's initial and present conditions, respectively.

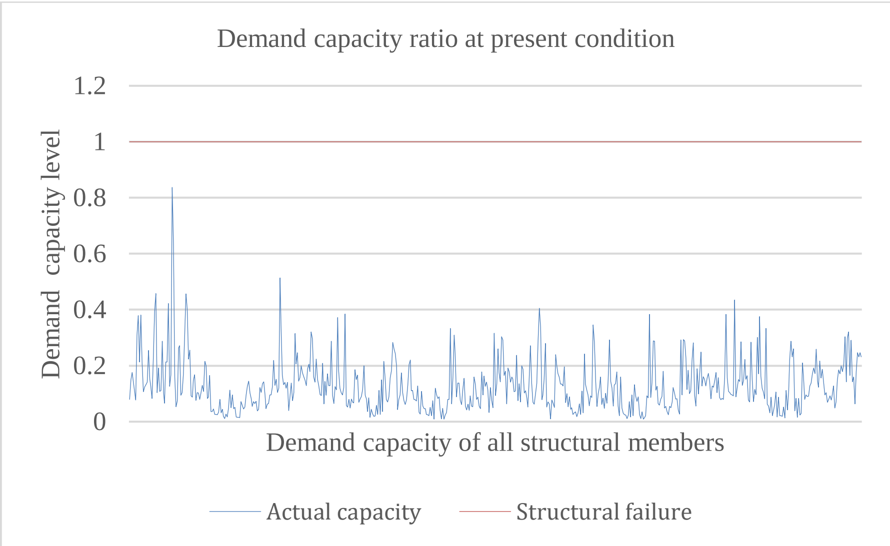

Figure 5. Demand capacity ratio of structural members at present condition.

Structural elements are considered severely damaged or collapsing if the DCR value found from linear static analysis exceeds the above values. **Figure 6** shows the comparison of the demand capacity ratio of the Structure at both initial and current conditions.

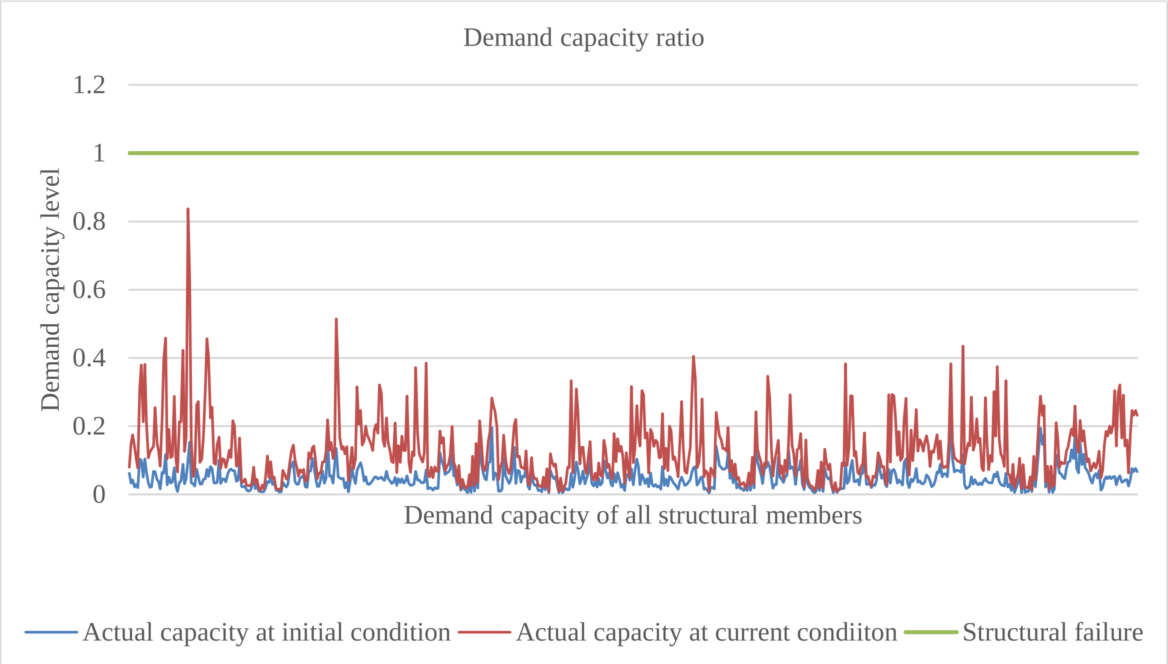

Figure 6. Comparison of demand capacity ratio of structural members.

4.2. Evaluation of deflection of the structure

In this study, the maximum developed deflection is 31.08 mm; in comparison, the maximum allowable deflection is 102.97 mm in the Structure's present condition. In the initial condition, the developed deflection is 19.23 mm. The developed displacements have been determined to be within the allowable range. The figures illustrate the maximum deviation between vertical and horizontal members about permitted displacements. **Figure 7** shows the developed deflection at the Structure's initial condition, while **Figure 8** shows the present condition.

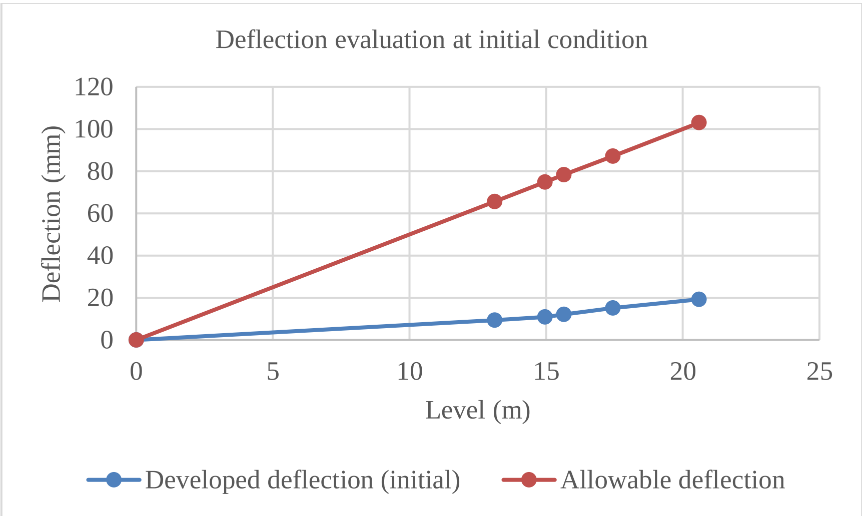

Figure 7. Evaluation of deflection at initial condition.

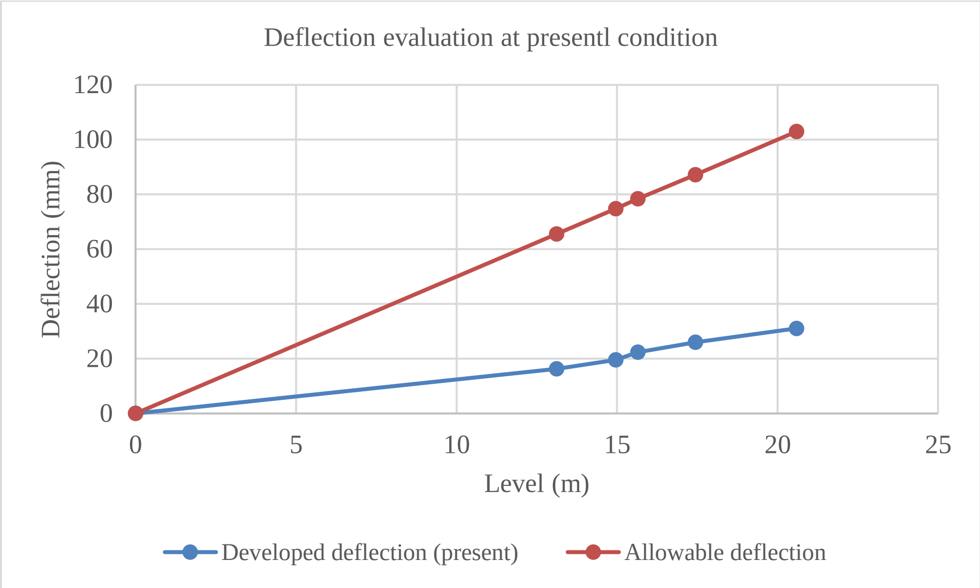

Figure 8. Evaluation of deflection at present condition.

4.3. Study on time history analysis

It is crucial to evaluate the time acceleration of an aging steel structure when performing dynamic analysis. Time acceleration sheds light on how a structure reacts to dynamic factors like operating loads or seismic activity. Acceleration has been studied for all nodes; data for node 174 has been presented and described below. In this Structure at node 174, for X acceleration, the maximum positive acceleration value has been found to be 105, and the maximum negative acceleration value has been found to be -101. **Figure 9** shows the time acceleration for the X-axis at node 174.

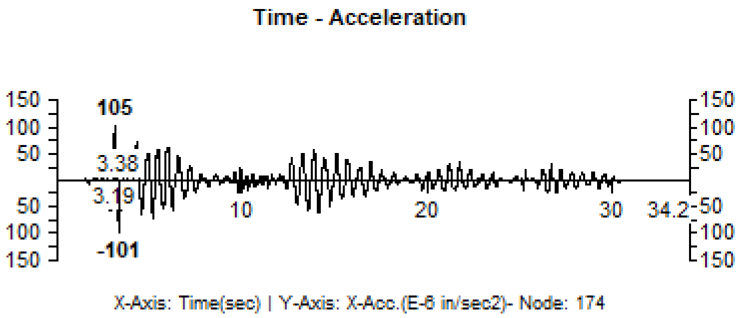

Figure 9. X-axis, X-acceleration at node 174.

For Y acceleration at node 174, the Maximum positive acceleration value is 23.6, and the maximum negative acceleration value is -21.5. **Figure 10** shows the X-axis Y-acceleration, while **Figure 11** shows the X-axis Y-acceleration.

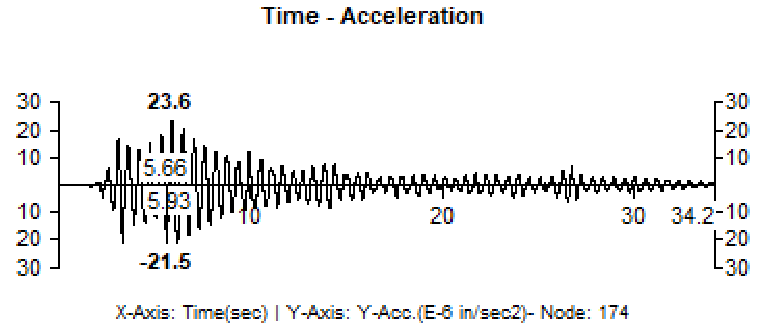

Figure 10. X-axis, Y-acceleration at node 174.

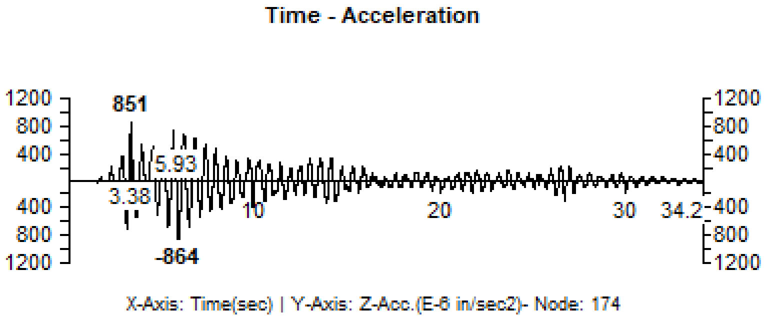

Figure 11. X-axis, Z-acceleration at node 174.

Evaluation of time-history analysis is necessary when assessing an existing structure, as they highlight how fluctuations in conditions can lead to substantial variations in acceleration. Time history analysis offers invaluable insights for informed decision-making regarding structural adaptations or remedial interventions.

4.4. Study on frequencies and mode shape

Tables 3 and **4** display the Structure's frequency and mass participation in its initial condition and present condition, respectively.

Table 3. Frequencies and mass participation of the structure at the initial condition.

Mode	Frequency (Hz)	Period (Seconds)	Participation X (%)	Participation Y (%)	Participation Z (%)	Type
1	2.490	0.402	0.002	0.005	35.048	Elastic
2	2.909	0.344	0.044	0.025	25.986	Elastic
3	3.195	0.313	34.439	0.053	0.019	Elastic
4	3.374	0.296	0.001	0.004	0.004	Elastic
5	3.417	0.293	30.629	0.000	0.025	Elastic
6	3.616	0.277	0.280	0.052	11.098	Elastic

Since lower mode forms are closer to the intrinsic frequency of the Structure, they include more mass than higher mode shapes, which correspond to shorter periods. The different modes of a structure are determined by the number of joints and their degrees of freedom.

Table 4. Frequencies and mass participation of the Structure at present condition.

Mode	Frequency (Hz)	Period (Seconds)	Participation X (%)	Participation Y (%)	Participation Z (%)	Type
1	2.141	0.467	0.001	0.003	35.061	Elastic
2	2.552	0.392	0.081	0.028	26.155	Elastic
3	2.717	0.368	2.097	0.063	0.000	Elastic
4	2.739	0.365	23.59	0.000	0.035	Elastic
5	2.966	0.337	34.11	0.000	0.001	Elastic
6	3.081	0.325	2.081	0.000	0.036	Elastic

The lower mode shapes are usually associated with more extended periods and capture the underlying frequencies of the Structure. **Figures 12** and **13** compare periods and frequencies at both conditions.

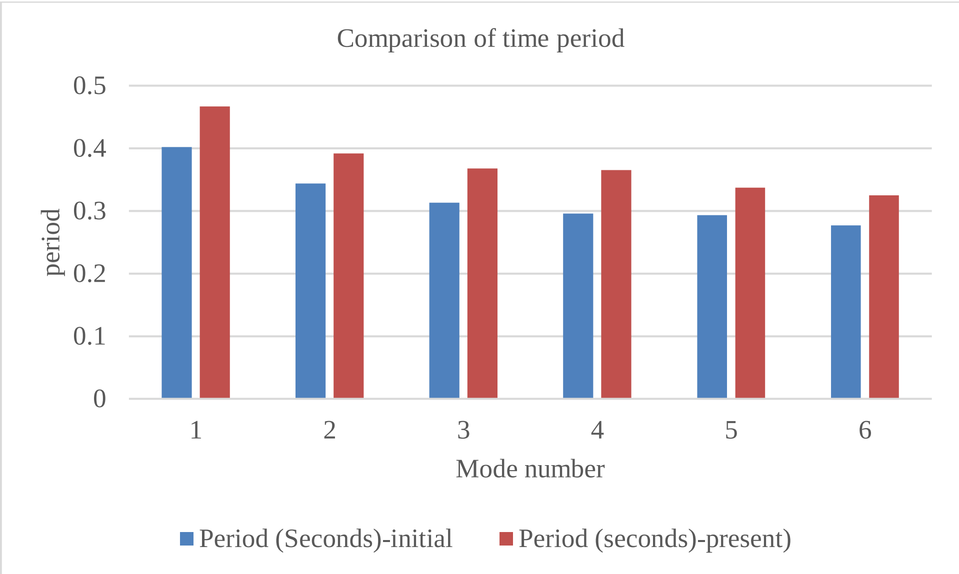

Figure 12. Comparison of the period at both conditions.

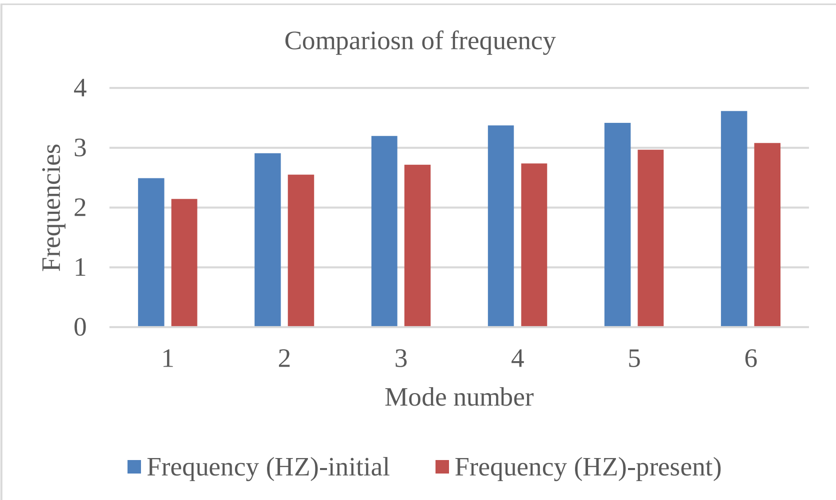

Figure 13. Comparison of frequency at both conditions.

In this study, modal analysis was conducted on two versions of the same Structure: the initial condition representing the new state of the Structure and the present condition representing the aged or current state.

The modal analysis focused on six mode shapes labeled mode-1, mode-2, mode-3, mode-4, mode-5, and mode-6. **Figures 14** and **15** show mode shapes 1 and 2, respectively.

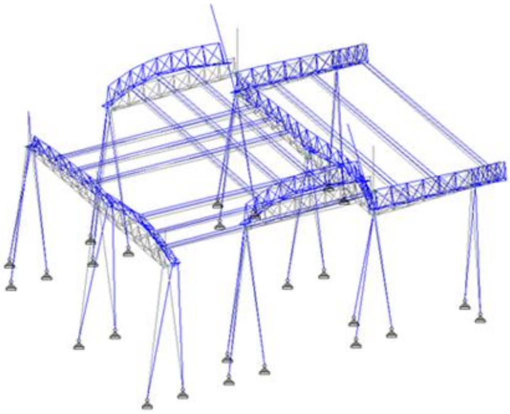

Figure 14. Mode shape 1.

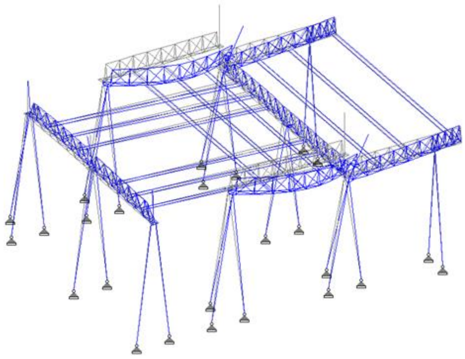

Figure 15. Mode shape 2.

The results revealed distinct differences in the mode shapes between the initial and present conditions. Each mode shape exhibited unique vibration patterns and deformations, providing valuable insights into the Structure's dynamic behavior under different loading conditions. **Figure 16** represents mode shape 3, while **Figure 17** displays the mode shape changes for mode 4.

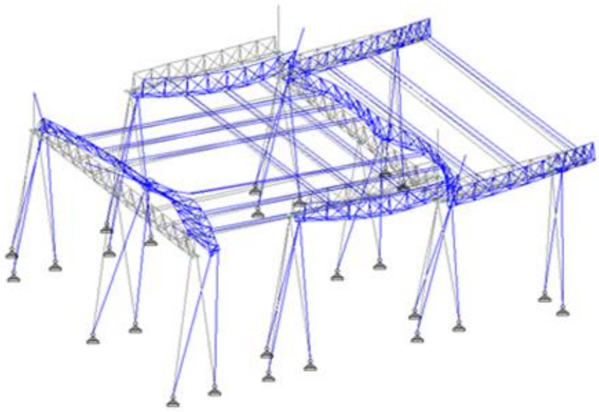

Figure 16. Mode shape 3.

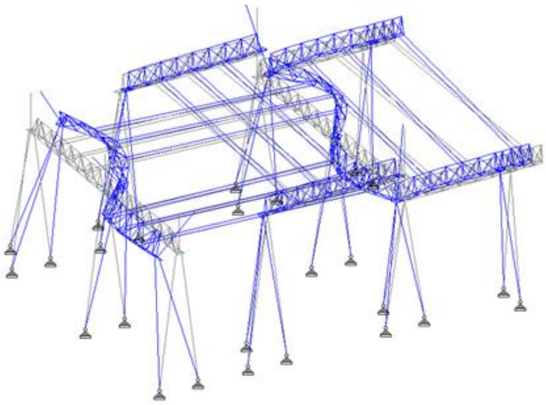

Figure 17. Mode shape 4.

As the number of modes rises, the structural behavior deviates farther from the fundamental natural frequencies. **Figures 18** and **19** show mode shapes 5 and 6, respectively.

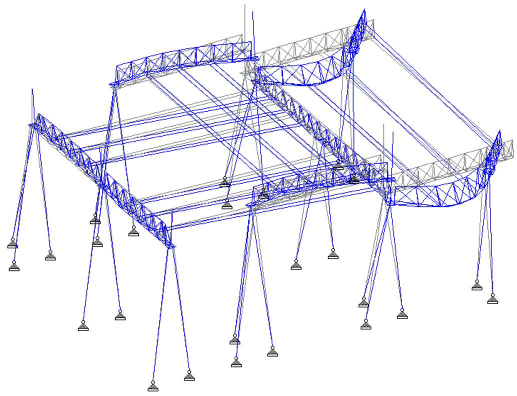

Figure 18. X-axis, mode shape 5.

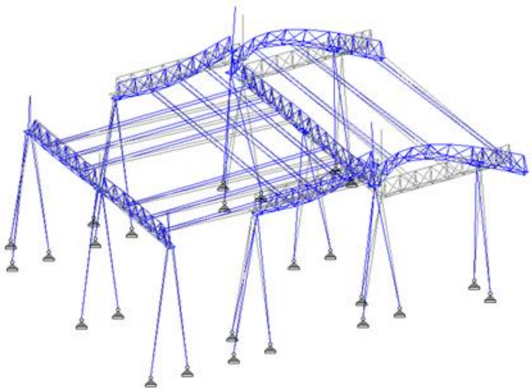

Figure 19. X-axis, mode shape 6.

Overall, the modal analysis results highlight the importance of considering dynamic characteristics and mode shapes when assessing structural integrity and performance. The differences between the initial and present conditions underscore the evolving nature of structural behavior and the necessity of regular assessments to ensure continued structural safety and reliability.

5. Conclusions

This research comprehensively analyzes the lateral load response of a steel-framed structure subjected to wind and seismic forces in its current condition.

1. SCR of all structural members has been found within the allowable limit utilizing the FEM and conducting extensive simulations.
2. The Structure's vertical and horizontal displacements have been found within the allowable limits according to the ASCE substation guidelines.
3. According to the findings, due to mass redistribution over time, the Structure has extended periods, leading to reduced stiffness and increased flexibility. The dynamic analysis comparing the current and previous states of the Structure supports this.
4. The findings demonstrate lower natural frequencies due to degradation of stiffness.

The findings highlight the importance of ongoing monitoring and timely maintenance to mitigate further degradation and extend the service life of such structures in harsh environments.

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Conflicts of Interest

The authors declare no conflict of interest.

Authors Contribution Statement

Kamal Hosen: Conceptualization; Kamal Hosen: Data curation; Kamal Hosen: Formal analysis; Md. Mia, Kamal Hosen: Investigation; Kamal Hosen, Md. Mia: Methodology; Md. Mia: Project administration; Md. Mia: Resources; Kamal Hosen: Software; Md. Mia: Supervision; Md. Mia, Kamal Hosen: Validation; Md. Mia, Kamal Hosen: Visualization; Md. Mia: Roles/Writing – original draft; Md. Mia, Kamal Hosen: Writing – review & editing.

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