NONLINEAR TIME-HISTORY ANALYSIS FOR RIGOROUS PERFORMANCE EVALUATION OF STEEL STRUCTURE IN SUBSTATION

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ABSTRACT

To transmit and distribute electricity from power generators to consumers, electrical substations are essential components of a power system. This research explores the seismic vulnerability of electrical substations, which, based on past earthquake incidents, are susceptible to damage from ground shaking, potentially disrupting power supply to consumers. Given the significant greenhouse gas emissions associated with construction materials, a sustainability-driven approach urges structural engineers to assess the cost-effectiveness of maintaining versus demolishing existing structures, necessitating a seismic performance analysis. The maintenance of aging substation structures is crucial. In sustaining a structure, determining the maximum load it can support at any given time requires design equations or numerical assessments. However, the need for design drawings makes obtaining input data challenging. To address this, input constraints are defined using non-destructive testing (NDT) or logical evaluations. This study focused on a steel substation in China and integrated a comprehensive site survey to gather structural data, measurements, and loading information. Using the finite element approach, the vulnerability of the steel structure is examined, considering the mass, stiffness, and geometry of substation components. The assumption of rigidly bonded steel contacts is made. Empirical equations and finite element analysis, along with a comparison with experimental data, validate predictions. The research aims to contribute insights into sustainable maintenance practices for aging substation structures amid resource constraints. The methods employed for performance evaluation are scrutinized for their effectiveness in assessing seismic resilience.

A seismic analysis comparison is performed on an existing steel structure via STAAD.Pro.-2023 software. The seismic analysis method in this study involves a nonlinear static investigation and a nonlinear time history dynamic analysis. Time-frequency, mode shape change, deflection in a different direction, and strength-capacity ratio have been observed for this structure.

Keywords: *Steel structure, substation, time-history analysis, progressive collapse, performance evaluation*

1. INTRODUCTION

These days, an inspection of an existing structure must occur once every five years. The amount of infrastructure in China that is more than 50 years old is rising. The Chinese authority has stated that in the next 20 years, the percentage of structures of this type will reach 60%. As a result, it is crucial to supply those buildings with efficient maintenance and assessment (Motonori et al., 2022). A substation comprises numerous interconnected systems of electrical paraphernalia mechanisms and subsidiary structures; some include power/contemporary converters, separate buttons, circuit rollers, modifiers, supporting paddings, and portal surrounds. There has been a lot of focus on the seismic performance of different single and coupled electrical equipment components (Huangbin et al., 2022). The practice of cold-formed steel (CFS) structures has enlarged significantly in recent years, both in residential and industrial settings. Its many benefits—including superior quality, ease of construction, and comparatively low weight—have made it a suitable substitute for traditional methods. Most electric power substations (EPS), mainly situated outside of municipalities, are built using hot-rolled steel angle truss constructions, which are far more costly and substantial (Mehran et al., 2018). Many analytical and experimental studies have been conducted in the last few decades to optimize the capacity of cold-formed steel sections in CFS configurations. Research (Pedreschi and Sinha, 2008) carried out a few experimental studies utilizing various configurations on full-sized samples to ascertain the effect of mechanical clinching in steel trusses. To regulate the samples' supreme load capacity and the connection failure machinery, Zeynalian (Zeynalian et al., 2016) also conducted an investigational inspection of cold-formed steel truss associates. Chang and Wu (Liang Chang and Zhigang Wu, 2011) examined the electrical grid's resilience to ground motion during earthquakes and assessed its susceptibility to cascading failures. For the purpose of evaluating substation resilience, essential resources include the quick response plan under cascading impact and the functional evaluation standard. The study of power system resilience optimization and seismic retrofitting was primarily conducted from two perspectives: technological and operational. While measures relate to emergency repair plans or resource transportation tactics, expertise includes situational awareness monitoring and equipment reinforcement. Even if they have nothing to do with maintaining, repairing, or upgrading a component, increasing redundancy and adding extra parts are nonetheless essential actions. Still, a lot of research has been done on how to make power systems more resilient to severe calamities (Xiao Liu, 2023). Rushan L. (Zhaoyang et al., 2022) established five categories for the substation's resilience, offering a set of guidelines for assessing the level of resilience. Additionally, they put forth a model that accounts for high-voltage electrical equipment, building weighting coefficients, and seismic intensity when calculating the buildings' resilience index. Apart from the substation's resilience study, another thing to think about is the financial benefit of seismic strategy. Since then, resistance-based design techniques for substation structures have received a lot of attention. The skeleton curves of recovery and the recovery scenario for the Los Angeles power system were created based on the post-earthquake retrieval prototype of the power structure constructed by Cagnan (Zehra et al., 2006).

Although numerous works have been done to evaluate the seismic performance of steel structures in substations, most of them are based on laboratory experiments and software simulation, including the mechanical characteristics of corroded steel, such as its strength, elastic modulus, ductility, stress-strain relationship, etc. More research needs to be done on these based on the real-site structure. The current study intends to assess the lateral enactment of the CFS truss system conducted by an accurate site survey and existing steel structures in the substation, containing an evaluation of their seismic reaction alteration influences and taking into account the benefits of CFS structures. Several site inspections have been conducted, and some non-destructive tests have been done in this study. The nonlinear dynamic response analysis of substations with structure-equipment interaction is studied in this paper. Time history analysis and changes in mode shape have been observed in this research.

2. METHODOLOGY

For this study, a substation structure in China has been used. An inspection of the site has been carried out to obtain precise site data. Due to safety concerns, entry inside the site was prohibited. We were assisted in carrying specific data, including vibration measurement data, by a few skilled substation workers who used vibration tools. An external visual inspection of the substation has been conducted. The substation authority's earlier plans and drawings served as the basis of all structural documents. Figure 1 demonstrates the photos of the site inspection.

Figure 1: Photo captured during site inspection

Structural analysis software STAAD.Pro-2023 has been used to generate a FEM model and analyze the structure. The structure has been analyzed using the ASCE load combination for the substation, taking into account 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. A pipe column and angle truss system with a cantilever truss make up 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. For the structure, nonlinear static, dynamic, and time history evaluations have been completed. Figure 2 shows the 3D structural model that has been collected from the software.

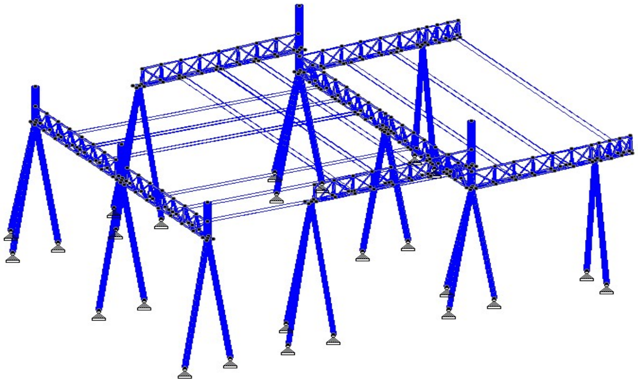

Figure 2: 3D Structural model of the substation's structure

2.1 Loading Criteria

The self-weight of the structure, 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 analysis of the structure (Leon Kempner, 2008).

The seismic strategy force, FE, can be computed using the following equation by applying an equivalent lateral force approach to the computation of structure earthquake loads (Leon Kempner, 2008).

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

Where W is the dead load (which includes entirely equipment that is strictly devoted and 50% of the weight of any involved cable), Sa is the strategy of supernatural response acceleration, I_{MV} is 1.0 for dominant single-mode behavior or 1.5 when multiple vibration modes are taken into consideration, R is the structure-response modification factor, I_{FE} is the importance factor for earthquake loads, and FE is the lateral energy practical at the center of severity of the structure or constituent.

The maximum loading is determined by the direction in which wind loads are applied to substation equipment, structures, and conductors (buses and wires). The following formula can be used to calculate the wind force (Leon Kempner, 2008):

$$F = QK_Z V^2 I_{FW} G_{RF} C_f A$$

Where V is the basic wind rapidity and the 3-s gust wind rapidity (miles per hour, meters per second), I_{FW} is the importance factor, G_{RF} is the gust response factor (for the structure and wire), C_f is the force coefficient, A is the predictable wind surface zone usual to the route of the wind (ft^2, m^2), and Q is the air mass factor, defaulting value = 0.00256 (0.613 SI). According to ASCE rules, load combinations have been applied, as shown in Table 1

Table 1: Design scenarios for ultimate strength and load features

Load Cases	Load Factors and Combinations
Case 1	$1.1\ D + 1.2\ WI_{FW} + 0.75\ SC + 1.1\ T_W$
Case 2	$1.1\ D + 1.2\ I_W I_{FI}{}^{a} + 1.2\ W_I I_{FIW}{}^{b} + 0.75\ SC + 1.1\ T_W$
Case 3	$1.1\ D + 1.0\ SC + 1.1\ T_W$
Case 4	1.1 D + 1.25 E (or EFS) + 0.75 SC + 1.1 TW

A structure's dead load is represented by D; stirring wind load by W; wind load in grouping with ice by W_I; wind load in grouping with ice by I_w; earthquake load by E_{FS}; earthquake load retorts from the first upkeep levied on the remaining portion of the structure by T_w; short-circuit load by SC; and significance dynamics (IFW, IFI, IFWI, and IFE) by I_F.

3. RESULTS AND DISCUSSION

Nonlinear static analysis and nonlinear dynamic analysis have been done, considering time history analysis and mode shape changes, to evaluate the safety performance of the structure. The LFRD design and analysis method was used for the strength capacity calculation of each structural member. ACD analysis methods have been used for the serviceability evaluation of the structure.

3.1 Study on Strength Capacity Calculation of the Structure

The strength capacity ratio (SCR) is used to analyze which structural element has exceeded its load-carrying capacity and potentially led to tolerant failure (Sonawane et al., 2013). The below equation is used to determine the SCR values based on the linear elastic static analysis.

$$SCR = M_{max} \ / \ M_p \tag{5}$$

Here, M_{max} equals the moment. Demand was intended using linear variable inert analysis from STAAD.Pro. and M_p equal the eventual moment ability (malleable moment) calculated for each structural member. The acceptance criteria of the structure are based on the demand-capital ratio limits. If the SCR is below 1.00, it has been considered safe; if it is more significant than 1.00, it has been considered an overstressed structural member.

$$Developed\ SCR < 1.00 = \ Safe$$

$$Developed\ SCR \ > \ 1.00 \ = Unsafe$$

Structural elements are considered severely damaged or collapsing if the DCR value found from linear static analysis exceeds the above values. This study's demand capacity ratio for all structural members was less than 1.00, as shown in Figure 3.

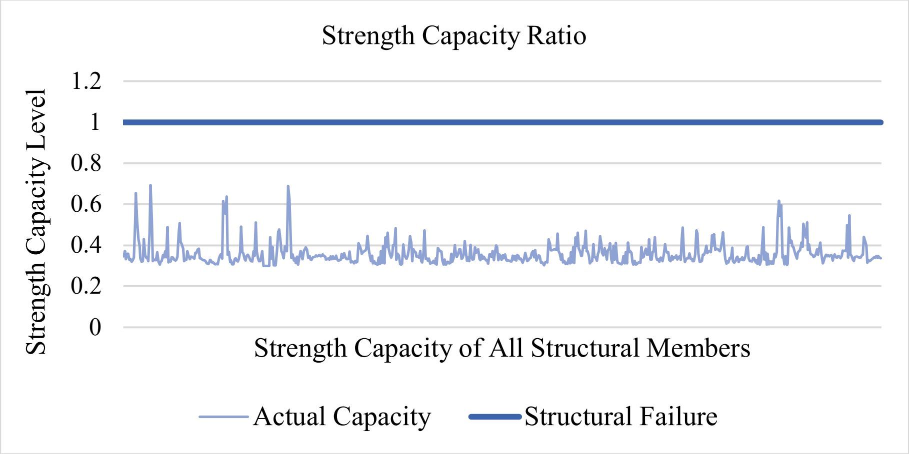

Figure 3: Calculation of strength-capacity ratio

3.2 Study on Deflection of the Structure

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, which can alter the way 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 (ASCE, 2000). Maximum deflections are determined by taking the upright distance, or span, of a standing member from the foundation support to the structure's plug of examination. Table 2 shows the acceptance criteria for deflection.

Table 2: Deflection criteria and acceptable limits of the structure (ASCE, 2000).

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

Figure 4 below illustrates the maximum deviation between vertical and horizontal members about permitted displacements. The developed displacements have been determined to be within the allowable range.

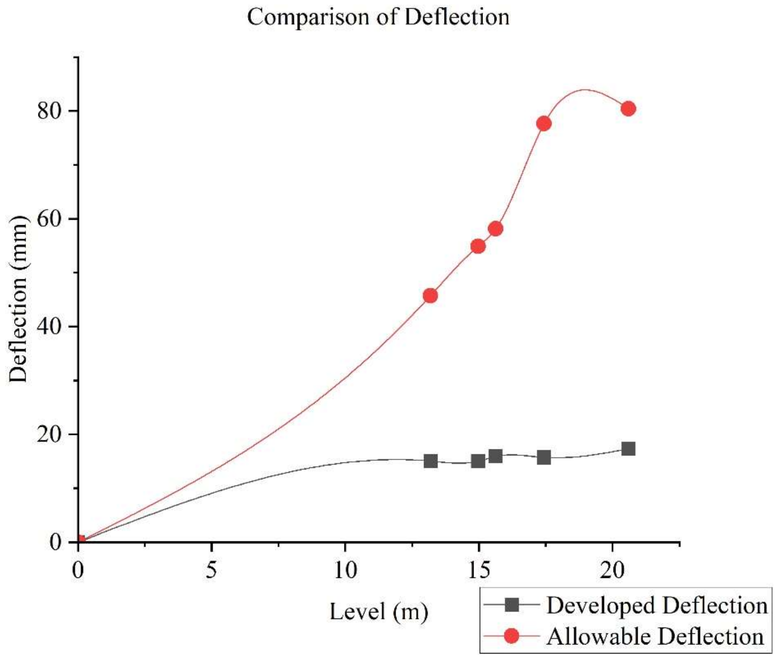

Figure 4: Deflection comparison of the structure

3.3 Study on Time History Analysis

The only method that can truly capture the performance of a structure throughout an earthquake is a nonlinear time history analysis (Si-Wei et al., 2016). The method considers the elastoplastic deformation of the structural element. It is founded on the thorough mathematical incorporation of motion discrepancy calculations (Lovepreet et al., 2023). Engineers can ensure a structure's durability and safety by evaluating its performance under intense loading situations, thanks to its 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.

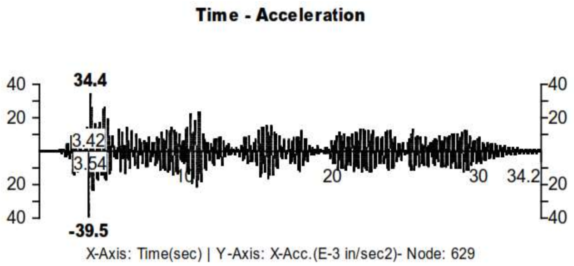

Figure 5: Time acceleration at the bottom of the truss

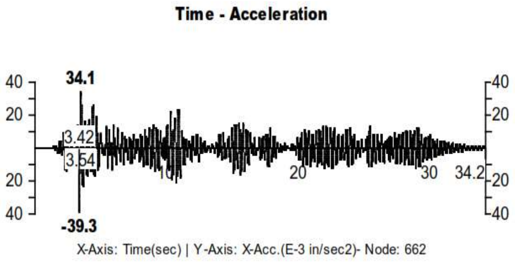

Figure 6: Time acceleration at truss and column joint area

Figure 5 and Figure 7 display the time acceleration at the bottom and top points of the truss, respectively. Figure 6 shows the column and truss joint accelerations. In contrast, figure 8 shows the time acceleration at the highest point of the column.

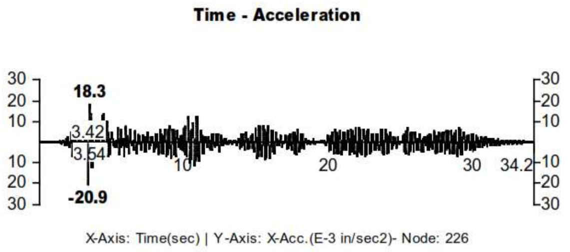

Figure 7: Time acceleration at the top of the truss

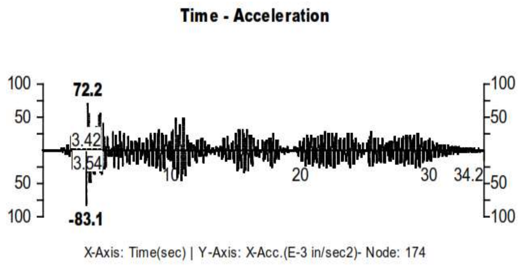

Figure 8: Time acceleration at the top of the column

3.4 Study on Frequencies and Mode Shape

The mode shape of a component is the deformation it would experience while vibrating at its natural frequency. A component exhibits deformation, shown by its mode shape, when it vibrates at its intrinsic frequency. This investigation has noted variations in mode form for several modes. Regardless of the frequency content of the excitation forces, a specific frequency can be linked to every mode shape of the excited structure. Table 3 shows the frequencies and mass participation of the structure.

Table 3: Frequencies and mass participations

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

Because these mode forms are closer to a structure's inherent frequency, the lower mode shapes (with a more extended period) have more significant mass involvement than the higher mode shapes (with a higher frequency). The quantity of joints and their degrees of freedom determine a structure's many modes. Lower-mode forms typically capture the inherent frequencies of the structure. More extended periods are usually found in lower-mode forms. The lower mode shapes (more extended period) involve more mass than the higher mode shapes (higher frequency) because these mode forms are closer to the inherent frequency of a structure. Examine structural behavior farther from the primary natural frequencies of the structure as the number of modes increases. Figures 9 and 10 show the changes in structure in mode shape number 1 and mode shape number 2.

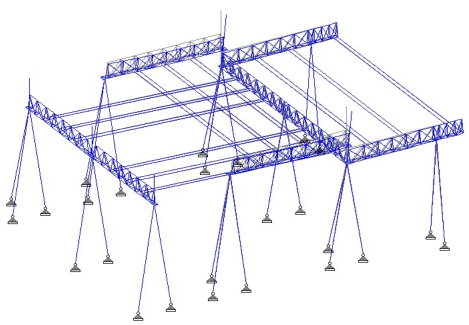

Figure 9: Mode Shape 1.

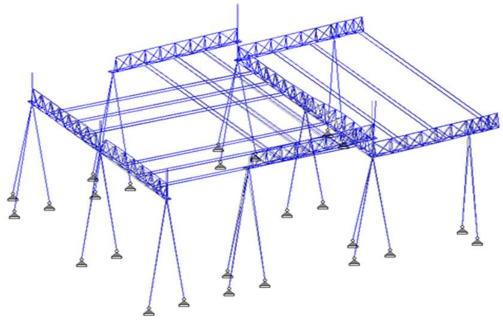

Figure 10: Mode shape 2

4. CONCLUSION

This paper presents an end-to-end seismic performance-based evaluation framework that relies on site- and substation-specific structural assessments to account for ground-motion duration impacts in realistic and practical engineering applications. STAAD.Pro-2023 computer program was utilized for nonlinear static and dynamic analyses of a steel-framed substation structure to evaluate progressive collapse potential. Comparative assessments with field experiment data confirm the structural safety of its current state. Multiple reaction modes were considered, including the plasticity of steel, geometric nonlinearity, and residual stresses. The nonlinear inelastic analysis program for steel frames was created and coded using the nonlinear solution technique. From the strength capacity ratio investigation, it has been determined that the steel structure under investigation is safe in its current state based on numerical and experimental simulations of the actual structure. When compared to hand calculations, the SCRs were calculated by the FEA software STAAD.Pro-nonlinear static analyses were closer to SCR limits. Therefore, FEA provided a more rigorous assessment of progressive collapse potential in this investigation. At each stage of the nonlinear time-history analysis, the plastic rotational deformation capacity of a part must be calculated using the necessary axial force and compared to the demand value. Future iterations of ASCE 41 or the ASCE Seismic Rehabilitation Guidelines should modify the statement that expresses this value at the moment of calculation for nonlinear dynamic analysis. The assessment of both vertical and horizontal deflection of the structure has been thoroughly conducted, revealing that the observed deflections are well within the established allowable limits outlined in accordance with the ASCE substation design guidelines. The structural performance has been analyzed and determined to comply with the specified standards, ensuring a secure and stable configuration aligned with the guidelines provided by ASCE for substation design.

5. RECOMMENDATIONS FOR FUTURE RESEARCH

The study's findings indicate that gradual collapse may be computationally simulated quite easily using finite-element computer programs like STAAD.Pro, SAP2000, ETABS, and SAFE. To further this research, it is advised to do the following in light of the observations and analytical results: To learn more about the mechanism of progressive collapse and prospective load redistribution systems in steel buildings; it would be beneficial to assess the possibility of progressive collapse in other irregular steel frame structures. It is recommended that structural performance be evaluated using a variety of techniques in future research.

ACKNOWLEDGEMENTS

The School of Civil Engineering at Southeast University (SEU), in particular, has supported and funded this project, which the authors would like to acknowledge. Additionally, Bulbul Ahmed and Hossain Ahmed are sincerely recognized for their help during this study.

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