Seismic Assessment of Electrical Equipment in Power Substations: A Case Study for Circuit Breakers[†]

Discussion by Eray BARAN*

ABSTRACT

Remarks are provided on the paper "Seismic assessment of electrical equipment in power substations: a case study for circuit breakers" by Kaatsız et al. on how allowable stresses are determined for steel framing members forming the support structure as well as the connection elements used in various parts of electrical devices.

Keywords: Seismic assessment, electrical equipment, seismic qualification.

INTRODUCTION

In their paper [1], the authors present a case study on seismic assessment of electrical equipment according to the new Turkish regulation. There are two issues in the paper that need further discussion. The first issue relates to the structural capacity of steel members that make up the device's support structure, while the second one concerns the capacity of connection elements, i.e., bolts and anchor rods. The subject paper is intended to serve as a guide for those who will use the new national code for seismic qualification assessment of electrical equipment. Therefore, it is crucial to clarify the issues related to the methods employed in the paper to ensure that such assessments are performed correctly.

CAPACITY OF STEEL MEMBERS

The paper adopts an approach where the stresses generated in various parts of the device under seismic and other applicable load effects are compared to the stress limits of the respective materials. While this approach is generally consistent with the allowable stress design method, it is crucial to understand how the allowable stress limits are determined. The authors seem to use the yield strength, reduced by a safety factor, as the allowable stress. Although this approach is correct for strength limit states associated with material yielding, it does not represent the actual strength of members in cases where other strength limit states are more critical. Therefore, it may lead to unsafe decisions regarding the seismic qualification of the device under evaluation. In the paper, the allowable stress for the steel members that make up the device's support structure are determined by dividing the material yield strength by a safety factor of 1.67, by referring to the Turkish Steel Design Code [2]. With the assumptions that these members are subjected to only axial load and have bolted

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connections at their ends, other applicable strength limit states that could determine the load capacity of such members are buckling, net section fracture, block shear, bearing, and tear out [2,3]. If there are additional bending moments present in members and/or if the members have welded connections at their ends, a different set of strength limit states would apply. In such cases, capacity corresponding to each limit state should be calculated for each steel member in the support structure. The smallest of these capacities, combined with the correct safety factor, should be used as the capacity of each member in seismic qualification assessment of the device.

Procedures to determine the capacity of steel structural members are provided in the Turkish Steel Design Code [2]. Chapter 7 relates to axial tensile capacity, Chapter 8 relates to axial compressive capacity, Chapter 9 relates to bending moment capacity, and Chapter 11 relates to the interaction between axial force and bending moment. For tensile members nominal axial force capacity corresponding to the limit state of net section fracture is determined with Eqn. 1. Nominal axial force capacity of compression members is determined with Eqn. 2. In these equations, Fu is tensile strength of steel, Ae is effective net section area, Fcr is critical buckling stress, and Ag is gross cross sectional area.

$$T_n = F_u \cdot A_e \tag{1}$$

$$P_n = F_{cr} \cdot A_g \tag{2}$$

For members under combined axial force and bending moment, interaction between these effects should be considered by using Eqn. 3. In this equation Fca is the axial stress capacity determined according to Eqn. 1 for tensile axial force and Eqn. 2 for compressive axial force, Fcbw and Fcbz represent, respectively the strong axis and weak axis bending stress capacities. Nominal bending moment capacity of members with a single angle cross section is taken as the smaller of the capacities from Eqns. 4-6. In these equations, My is yield moment capacity and Mcr is elastic lateral torsional capacity.

$$\left|\frac{f_{ra}}{F_{ca}} + \frac{f_{rbw}}{F_{cbw}} + \frac{f_{rbz}}{F_{cbz}}\right| \leq 1.0 \tag{3}$$

$$M_n = 1.5M_y \tag{4}$$

$$M_n = \left[1.92 - 1.17\sqrt{\frac{M_y}{M_{cr}}}\right] M_y \tag{5}$$

$$M_n = \left[0.92 - 0.17\sqrt{\frac{M_y}{M_{cr}}}\right] M_{cr} \tag{6}$$

CAPACITY OF STEEL CONNECTION ELEMENTS

The second issue that needs to be addressed concerns the allowable stress of connection elements, i.e., bolts and anchor rods. In the paper allowable stress values for these elements are determined by dividing the material yield strength by a safety factor of 2.0. However, as stated in current steel design codes [2,3], material yielding is not considered a strength limit state for these elements; instead, their capacities should be determined based on the fracture limit state. Furthermore, for the type of electrical equipment studied in the paper, significant shear forces usually develop in connection elements, in addition to tensile axial force. In such cases, evaluating the structural safety of these elements considering only tensile forces would lead to unsafe conclusions. The correct approach to determine the safety of connection elements should account for the interaction between shear and tensile axial forces and consider the fracture limit state under both effects.

Structural capacity calculation of steel connection elements and connected parts is outlined in Chapter 13 of the Turkish Steel Design Code [2]. Accordingly, nominal tensile and shear force capacities for bolts and anchor rods are determined with Eqns. 7 and 8, respectively. In the presence of combined tension and shear force, interaction defined by Eqn. 9 should be utilized. In these equations, Fnt is nominal tensile strength, Fnv is nominal shear strength, frt and frv are, respectively tensile and shear stresses on the bolt, Ab is unthreaded cross-sectional area, and Ω is factor of safety, which has a value of 2.

$$R_{nt} = F_{nt} \cdot A_b \tag{7}$$

$$R_{nv} = F_{nv} \cdot A_b \tag{8}$$

$$\frac{\Omega \cdot f_{rt}}{F_{nt}} + \frac{\Omega \cdot f_{rv}}{F_{nv}} \leq 1.3 \tag{9}$$

Block shear, bearing and tear out are other connection related strength limit states that should be taken into account when determining the axial force capacity of steel members. Nominal block shear capacity is determined with Eqn. 10, where Agv, Anv and Ant are respectively gross shear area, net shear area and net tension area, Ubs is shear lag coefficient. Capacity corresponding to bearing and tear out around bolt holes is determined with Eqn. 11. In this equation, lc is clear distance in the direction of force between two holes or between a hole and edge of the member, t is thickness of the member, d is dolt diameter.

$$R_n = 0.6F_u \cdot A_{nv} + U_{bs} \cdot F_u \cdot A_{nt} \leq 0.6F_y \cdot A_{gv} + U_{bs} \cdot F_u \cdot A_{nt} \tag{10}$$

$$R_n = 1.2l_c \cdot t \cdot F_u \leq 2.4d \cdot t \cdot F_u \tag{11}$$

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ANSI/AISC 360-22 Specification for Structural Steel Buildings. American Institute of Steel Construction, 2022.

Authors' Closure

ABSTRACT

This reply provides clarification following comments by Eray Baran on our recent paper in Turkish Journal of Civil Engineering, 49-68 [2024] titled as "Seismic Assessment of Electrical Equipment in Power Substations: A Case Study for Circuit Breakers".

Keywords: Seismic assessment, electrical equipment, power station, circuit breaker, seismic qualification.

1. INTRODUCTION

First, the authors of the article would like to thank Dr. Eray Baran for his comments on the paper titled *"Seismic Assessment of Electrical Equipment in Power Substations: A Case Study for Circuit Breakers"* [1].

Baran [2] stated that there are two issues in the paper that need further discussion. The first issue relates to the structural capacity of steel members that make up the device's support structure, while the second concerns the capacity of connection elements, i.e., bolts and anchor rods. The next two sections in the paper are devoted to responding to the issues raised by the author. The last section gives the final remarks. We hope that the replies clarify the issues related to the methods employed in the paper, ensure that such assessments are performed correctly, and serve as an additional guide for those who will use the new national code for the seismic qualification assessment of electrical equipment [3].

The scope of our paper [1] is primarily focused on calculations performed for the seismic qualification of the high-voltage hardware itself rather than the structural system. To maintain focus and brevity, we concentrated our discussion on the stress demands of these critical components. It should be noted that the seismic qualification study was performed for all the subcomponents of the circuit breakers presented in the paper by considering the failure modes for steel members and anchors. In this reply, the discussion is expanded to include these calculations to address the issues raised by Baran [2].

2. CAPACITY OF STEEL MEMBERS

In response to the statements in Kaatsız et al. [1], Baran [2] stated that, although employing the yield strength reduced by a safety factor as the allowable stress is correct for strength limit states associated with material yielding, it does not represent the actual strength of members in cases where other strength limit states are more critical. Therefore, this approach may lead to unsafe decisions regarding the seismic qualification of the device under evaluation. Other applicable strength limit states that can determine the load capacity of such members have been listed as buckling, net section fracture, block shear, bearing, and tear-out. The author defines the appropriate procedure as follows: First, the capacity corresponding to each limit state should be calculated for each steel member in the support structure. Then, the smallest of these capacities, combined with the correct safety factor, should be used as the capacity of each member in the seismic qualification assessment of the device.

As discussed, the capacity checks for the steel members constituting the support structure were performed during the seismic qualification study; however, the obtained results were omitted from the paper [1] for reasons previously explained. For explanatory purposes, we present the results for the 1-pole circuit breaker. The allowable tensile strength and the computed maximum tensile load demands on the steel members constituting the support structure are provided in Table 1.

Table 1 - Comparison of allowable tensile strength and maximum loads of steel members in the support structure

Steel Member	Allowable Tensile Strength (kN)	Maximum Tensile Load (kN)
80x80x8 mm	171.7	141.8
65x65x5 mm	60.0	27.1
60x8 mm	31.1	9.6

Similarly, maximum compressive load demands on these members are compared with their corresponding capacities in Table 2. It was determined that inelastic buckling behavior is expected for the steel sections given in Table 2 due to the relatively short spans of the support structure. It should be noted that 60x8 mm steel members exhibit negligible compressive load demands; hence, allowable compressive load comparisons were not performed for these members. The compressive load demands were determined to be well under the calculated allowable capacities.

Table 2 - Comparison of allowable compressive strength and maximum loads of steel members in the support structure

Steel Member	Allowable Compressive Load Capacity (kN)	Maximum Compressive Load (kN)
80x80x8 mm	159.8	132.7
65x65x5 mm	168.6	52.1

The combined effects of axial load and bending moment demands calculated according to the Turkish Steel Design Code [4] were also computed, and their interaction was evaluated as discussed by Baran [2]. The results are presented in Table 3 for the most critical angle sections of the steel support structures (80x80x8 mm), where the bending moment demands are greatest. The tensile load and compression load effects were considered separately. Consequently, the investigated members are determined to be safe under the combined interaction of axial loads and bending moments.

Table 3 - Evaluation for the effects of combined axial load and bending moment (≤1.0) on 80x80x8 mm angle section steel members in the support structure

Steel Member	For Tensile Axial Force	For Compressive Axial Force
80x80x8 mm	0.8	0.9

The force demands presented in Tables 1–3 were calculated by considering the most critical load demands determined according to the load combinations utilized in our paper [1]. They represent the combined effect of seismic, service, and dead loads acting on the hardware. It can be deduced that the structural members of the steel support are safe when analyzed using the allowable stress design approach, as detailed in contemporary steel design codes [4, 5]. This conclusion is expected in light of the results detailed in our study such that the highest stress demands are observed in the terminal regions of high voltage hardware due to the cantilever behavior of the whole system under seismic action [1]. The steel support structures experience lower strain compared to the porcelain equipment.

3. CAPACITY OF STEEL CONNECTION ELEMENTS

The second issue raised by the author that needs to be addressed relates to the allowable stress of connection elements, i.e., bolts and anchor rods. Dr. Baran states that material yielding is not considered a strength limit state for steel connection elements; instead, their capacities should be determined based on the fracture limit state, as stated in current steel design codes [4, 5]. Furthermore, for the type of electrical equipment studied in the paper, significant shear forces usually develop in connection elements, in addition to tensile axial forces. The author adds that, in such cases, evaluating the structural safety of these elements while considering only tensile forces could lead to unsafe conclusions. Hence, the author proposes the correct approach to determine the safety of connection elements as accounting for the interaction between shear and tensile axial forces and considering the fracture limit state under both effects.

The bolts connecting the sections in the steel support structure are of the M16-8.8 type. Shear forces predominantly act on the connections within the support structure due to the response characteristics of the system under the applied loads. Therefore, shear capacities for the bolts and block shear capacities for the bolted connections in the support structure were checked, and the results are given in Tables 4-5. As shown in the comparison of demands and shear force capacities, the bolted connections of the support structure are determined to be safe under the considered loading.

The circuit breaker hardware (porcelain isolator) is attached to the steel support structure via a connection plate secured by four M24-8.8 type bolts at its four edges, as detailed in our paper [1]. The circuit breaker mechanism and the porcelain isolator hardware are connected to each other and deform as a cantilever structure under the considered loading. As a result, axial and shear forces develop in the M24-8.8 bolts due to bending moment demands at the base of the hardware. The resulting loads and the corresponding capacities for these bolts are compared in Table 6. The computed coefficient representing the interaction between these loads [2] is also provided in Table 6. Based on the results, the seismic performance of the connection bolts is determined to be satisfactory.

Table 4 - Capacity evaluation of M16-8.8 connection bolts in the support structure

Connection	Allowable Shear Capacity (kN)	Maximum Shear Load (kN)
Between 80x80x8 mm and 65x65x5 mm steel members	144.8	52.1
Between 80x80x8 mm and 60x8 mm steel members	36.2	20.9

Table 5 - Evolution of block shear capacity of M16-8.8 connection bolts in the support structure

Connected Steel Member	R_n (kN)	Maximum Load (kN)
80x80x8mm	109.6	10.0
65x65x5 mm	29.2	27.0

Table 6 - Capacity evaluation of M24-8.8 bolts in the isolator connection plate

Connection	R_{nt} (kN)	R_{nv} (kN)	f_{rt} (kN)	f_{rv} (kN)	Check (≤ 1.3)
Isolator connection plate	271.4	162.9	5.91	74.4	0.96

We consider that the capacity checks presented in Tables 4-6 are expected to be satisfied for a structure that is designed through a structural design by considering the contemporary steel design codes and associated seismic load requirements. The failure modes for connections and bolts are checked for possible failure modes and the resulting bolt dimensions are determined accordingly during the design phase of the high voltage hardware. Therefore, the satisfactory performance in terms of seismic qualification requirements is within the expectations of the authors.

4. FINAL REMARKS

Following the discussions in the previous sections, we would like to conclude that the seismic performance of the circuit breakers inspected in the scope of our study is satisfactory in light of the issues raised in the discussion paper [2]. It should also be noted that structural components, such as steel sections or connections of high-voltage equipment, are designed by utilizing contemporary steel design codes under the combined action of several load cases, such as dead, service, wind, and seismic action. Therefore, it is reasonable to expect that these components will easily satisfy the seismic qualification criteria. The same conclusion may not apply to high-voltage hardware, such as porcelain insulators or circuit breaker mechanisms, as they are designed and manufactured for electromechanical requirements rather than load cases such as seismic action. Hence, evaluating the stress demands on this hardware under seismic loads may deserv a priority over regular capacity checks for structural steel components from seismic qualification perspective. Otherwise, this may shift the focus away from the critical components while performing a seismic qualification study.

We acknowledge that the allowable capacity controls stated in the discussion paper [2] should indeed be performed for structural components of high-voltage equipment. We also consider that the main focus of a seismic qualification study, from an academic point of view, is the investigation of the stress demands on high-voltage components under the considered seismic actions. In light of this perspective, the main objective of our paper [1] was to document a systematic approach, as outlined in TEC-PS [3], to compute and compare the seismicity induced stress demands on electromechanical hardware with allowable capacities within the limited length of the manuscript. We would like to extend our thanks again to the author of the discussion paper [2] for giving us the opportunity to provide further results from our study and clarify specific points about our research.

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