Seismic Performance Factors of Reinforced Concrete–Steel Composite Air-Cooled Condenser Support Structures

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ABSTRACT

Reinforced concrete–steel composite structures supporting air-cooled condenser (ACC) systems in power plants are critical components of power generation infrastructure. Since many of these facilities are located in seismic-prone regions, a comprehensive evaluation of their nonlinear seismic behavior is essential to ensure reliable performance under extreme loading conditions. This study investigates the nonlinear response of these specialized industrial structures to determine key seismic performance parameters, including the response modification factor (*R*), ductility factor (*μ*), and overstrength factor (*Ω*), while identifying their governing failure mechanisms. For this purpose, eleven structural configurations representing common geometric and constructional characteristics of power plant projects were designed, numerically modeled, and evaluated. To characterize the nonlinear behavior of the structures, nonlinear static (pushover) analyses were performed in two orthogonal directions. Subsequently, one representative configuration was selected and assessed through nonlinear time-history analysis to investigate its response under biaxial seismic excitation. The results indicate that the average response modification factor (*R*) of the investigated structures is 7.49, with more than 90% of the calculated values falling within the range of 6.0 to 9.0. Furthermore, the average overstrength and ductility factors were obtained as 1.77 and 4.50, respectively. Evaluation of plastic hinge formation patterns revealed that nonlinear behavior primarily initiates at the bases of the reinforced concrete columns; however, the most critical hinges, in terms of approaching failure limits, develop in the upper brace-to-column connection regions. These regions play a decisive role in controlling the overall structural stability and progression of damage. The findings of this study provide a technical basis for refining seismic design coefficients and improving design provisions for future ACC support structures in power plant projects.

KEYWORDS

Power plant cooling structures, Nonlinear time-history analysis, Nonlinear static analysis, Seismic performance parameters, Failure mechanism.

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Introduction

Air-cooled condensers (ACCs) are increasingly used in thermal and combined-cycle power plants, particularly in water-scarce regions [1]. Their supporting structures are large-span, elevated RC–steel systems comprising hollow RC columns, steel girders and braces, fan decks, A-frames, and wind-wall components. Concentrated equipment loads and nonuniform mass and stiffness distributions can result in significant translational, torsional, and bidirectional seismic responses [2–4]. Previous studies have shown that nonlinear behavior is mainly associated with RC columns and brace-to-column regions, while torsional effects and the interaction between structural components can substantially influence seismic response [3–5].

Despite these investigations, dedicated seismic performance factors for RC–steel composite ACC support structures have not been established. In particular, the applicability of response modification factors developed for conventional RC or steel systems remains uncertain because ACC supports have different load-resisting mechanisms, geometric characteristics, equipment loading, and force-transfer mechanisms. The novelty of the present study is the quantitative evaluation of the response modification (R), ductility (μ), and overstrength (Ω) factors for a representative range of Iranian RC–steel composite ACC support structures. Eleven structural configurations are investigated through 22 nonlinear pushover analyses, their governing plastic-hinge mechanisms are identified, and supplementary nonlinear time-history analyses are performed to examine the consistency of the observed nonlinear behavior and the influence of simultaneous horizontal excitation.

Methodology

Eleven three-dimensional ACC support models were investigated, including six actual Iranian power-plant structures and five supplementary configurations with different bay arrangements and perimeter cantilevers. The models were developed in SAP2000 and included P–Δ effects and the principal gravity, equipment, wind, seismic, thermal, and mechanical loads. Initial seismic design followed Iranian Standard 2800 and relevant AISC and ACI provisions [6–8]. Six representative hollow RC column sections were separately modeled in OpenSees using their actual geometry and reinforcement. Cyclic analyses under axial gravity load were used to derive nonlinear column responses. The numerical model was validated against experimental results for a hollow rectangular RC pier [9], with differences of approximately 1.6% and 6.1% in positive and negative peak base shear, respectively.

The validated hysteretic responses were idealized as backbone curves and incorporated into SAP2000 using interacting P–M2–M3 plastic hinges. Nonlinear static pushover analyses were performed in both principal directions, resulting in 22 capacity curves. Four alternative capacity-curve idealization procedures were compared, and the procedure producing the lowest dispersion with a relatively conservative estimate of R was selected. One representative model (Model 2) was also subjected to nonlinear time-history analysis using the Roudbar–Manjil earthquake record at PGA levels of 0.35g, 0.5g, and 2g, considering both single-component and simultaneous excitation in the X and Y directions. These dynamic analyses were used only for supplementary qualitative validation and were not used to determine R, μ, or Ω.

Results and Discussion

The four capacity-curve idealization procedures produced mean R values of 8.12, 9.38, 7.49, and 9.38, with coefficients of variation of 19.37%, 17.25%, 15.68%, and 17.25%, respectively. The third procedure was selected because it provided the lowest dispersion.

Table 1. Statistical summary of the seismic performance factors

Parameter	Mean	Standard deviation	Observed range
R	7.49	1.17	4.74–9.35
μ	4.50	0.71	2.84–5.61
Ω	1.77	0.033	1.73–1.86

The selected procedure yielded mean values of R=7.49, μ=4.50, and Ω=1.77. The R values ranged from 4.74 to 9.35, with more than 90% between 6 and 9. The relatively small variation in Ω (1.73–1.86) compared with R indicates that differences in R were governed primarily by ductility. Variations in structural configuration, lateral stiffness distribution, redundancy, and distribution of inelastic deformation were the main factors affecting the results, with no clear monotonic relationship between structural weight and R.

The mean R of 7.49 is numerically close to the value of 7.5 specified for special RC moment frames in Iranian Standard 2800 [6]. However, this numerical similarity does not imply behavioral equivalence because ACC supports have a distinct RC–steel load-resisting system, concentrated equipment loads, and different force-transfer mechanisms. Therefore, R=7.49 should be regarded as a technical basis for developing dedicated seismic provisions rather than as direct justification for adopting the existing code coefficient.

The nonlinear response generally initiated near RC column bases, whereas the most critical hinges in terms of progression toward severe damage were concentrated in the upper brace-to-column connection regions. Across the 22 analyses, the first plastic hinge developed at approximately 28–55% of peak base shear, and in more than 72% of the analyses first yielding occurred at approximately 40–55% of peak resistance. The critical behavior of the upper connections is attributed to concentrated brace forces and simultaneous axial-force, shear, and biaxial-bending demands in the RC columns. These regions therefore require particular attention to force transfer, local detailing, and stress concentration.

The nonlinear time-history analyses showed that bidirectional excitation became increasingly important in the nonlinear response range. At 0.35g and 0.5g, the response remained predominantly elastic and the difference between single- and two-component excitation was limited. At 2g, simultaneous X- and Y-direction excitation increased the maximum deck displacement from 178.8 to 252.0 mm, corresponding to an increase of approximately 41%, while the number of plastic hinges increased from 20 to 24. This enhanced response was associated with simultaneous translational and torsional effects, P–M2–M3 interaction, stiffness degradation, and redistribution of internal forces.

Conclusions

The seismic performance of 11 RC–steel composite ACC support structures was evaluated through 22 nonlinear pushover analyses and supplementary nonlinear time-history analyses. The principal conclusions are:

- The selected capacity-curve idealization yielded R=7.49, μ=4.50, and Ω=1.77, with R ranging from 4.74 to 9.35 and more than 90% of the values between 6 and 9.
- The variation of R was governed primarily by ductility and was influenced by structural configuration, stiffness distribution, redundancy, and the distribution of inelastic deformation.
- Although R=7.49 is numerically close to the value of 7.5 in Iranian Standard 2800, the different structural mechanisms do not justify direct equivalence. The obtained value can instead provide a basis for developing dedicated seismic provisions for ACC support structures.
- Nonlinear response generally initiated at column bases, whereas the most critical hinges developed in the upper brace-to-column connection regions, emphasizing the importance of their force-transfer capacity and local detailing.
- R=7 may be considered a conservative preliminary design value for the investigated class of structures, while configuration-specific nonlinear analysis is recommended where more accurate seismic assessment is required.

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