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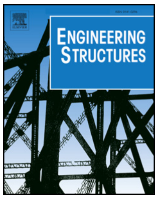

Computational assessment of the seismic behavior of steel stairs

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ABSTRACT

Stairs are an essential nonstructural system within buildings, providing egress to occupants as well as much needed access for emergency responders following an extreme event, such as an earthquake. Unfortunately, past earthquakes continue to reveal that these displacement-sensitive systems are highly vulnerable to damage and collapse. In this paper, high fidelity finite element models are developed and exercised in an effort to advance understanding of the seismic behavior of steel stairs under pseudo-static displacement loading indicative of earthquake-induced building movements. The proposed modeling approach is first validated through comparison with a set of experimental data and subsequently extended into a parametric study to broaden the range of stair configurations and details. In particular, the effect of story height, connection and landing details, and geometry on the behavior of the system is studied. Parametric analysis results indicate that the static force and displacement response of the stairs are sensitive to these key design parameters. Importantly, stair-to-buidling connections are subjected to large stress and strain demands under lateral displacement loading, as such their capability to maintain connectivity during an earthquake is crucial for robust seismic performance and hence continued functionality of the stair as a system.

1. Introduction

Stairs are a primary means of egress in buildings. They must remain operable following a strong-intensity earthquake and any ensuing post-earthquake events to support occupant evacuation and emergency response [1,2]. Stairs typically span from floor to floor in a building and therefore are subject to multiple-support dynamic excitations induced by the building during an earthquake. However, their structural response is complex due to the variability in spatial geometry, material, and construction details. Stiff and heavy stairs may even detrimentally interact with the supporting structure and thus modify the seismic response of the supporting structure [3]. Although stairs within a building virtually perform as structural systems from the design perspective, they are often considered within the category of nonstructural components in practice. The seismic design strength of a stair system may be readily estimated using code provisions [4], however their seismic performance is more significantly dictated by the differential displacements induced by their multiple attachment points to the building. Detailing stair systems with sufficient deformability to accommodate the expected floor-to-floor seismic drifts, however, remains a challenge due to limited knowledge regarding their structural behavior under lateral loading. This is further complicated by their complex geometries and variations of specific connection details in practice. As a result, stair systems continued to suffer severe damage and even collapsed in past earthquakes (e.g., [5–8]). Indeed, earthquake-induced damage to stairs continues to cause disruption of building functionality, delayed rescue operations, and even life safety hazards.

Experimental investigations of the seismic behavior of stair systems have occurred only in a few recent efforts. These studies include pseudo-static component tests of full-height reinforced concrete straight-run stairs [9] and full-scale prefabricated steel stairs in a scissors configuration [10]. In addition, a recent shake table test program investigates the system-level seismic behavior of a prefabricated stair system installed within a full-scale building [11,12]. These studies have advanced the state of understanding regarding the seismic behavior of stair systems. Research of this kind, however, is limited in occurrence due to its tremendous cost. To complement these experimental efforts, computational studies are important as they offer a cost-effective alternative to expand experimental findings. Recent computational studies have incorporated stair systems into numerical modeling of the seismic response of buildings in an effort to understand the effect of the stair system on the building response (e.g., [13,14]). It is noted, however, that the capability of the models to capture the seismic response of stairs in a system-level numerical simulation, in particular when the stairs are subjected to significant inelastic deformation during high-intensity earthquake excitations, has not been extensively investigated. Moreover, any effort to conduct numerical simulations requires validation against experiments, however the previous paucity in such data

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has precluded an expanse in numerical simulations as well.

To this end, this paper presents a comprehensive computational study to investigate the seismic behavior of prefabricated steel stairs using detailed three-dimensional finite element models. The models are implemented using the general-purpose finite element software *LS-DYNA* [15,16]. It is noted that a rather rigorous three-dimensional finite element modeling strategy is adopted in an effort to comprehensively capture subtle behavioral aspects of the stair as a system, when key design parameters are varied. The objectives of this study are: (1) to develop finite element models of prefabricated steel stairs that are capable of capturing their global response and local behavior as well as validate the effectiveness of the modeling strategies via comparisons with prior experimental studies [10], and (2) to conduct a parametric assessment of the seismic behavior of prefabricated steel stairs considering a broad range of design parameters commonly found in practice.

The present study focuses on the seismic behavior of the stairs under uniaxial pseudo-static displacement loading. It is assumed that the effect of dynamic loading does not substantially impact the stair response during an earthquake, and as such equivalent static cyclic displacement loading may be applied, due to the following two considerations: (1) the fundamental frequencies of these steel stairs are likely much higher than those of multi-story buildings, thus avoiding excessive acceleration amplification of the stairs [11], and (2) the dynamic inertial forces of these light-weight stairs is small compared with the pseudo-static forces induced by differential displacements. As such, the implications of heavier stairs or stairs with natural frequencies more closely tuned with that of its supporting building are outside of the scope of the present paper. In addition, it is noted that although the stairs are subjected to bi-directional (or tri-directional) floor-to-floor differential displacements during real earthquakes, the scope of the present study is focused on understanding their critical response characteristics under uniaxial displacement loading applied in the horizontal directions. The effects of multi-directional earthquake loading may be the subjects of future studies.

2. Model description

Although stairs vary in aspects such as geometric configuration and construction material, prefabricated steel stairs in a scissors configuration are considered as the prototype stairs in this study. This type of stair system is commonly used in practice and characterized by complex structural behavior, in particular torsional response. Moreover, the prefabricated scissors-type steel stairs were investigated in two recent experimental studies [10,11]. These experiments offer a baseline configuration and other aspects of the prototype stairs considered in the present numerical study. As shown in Fig. 1, the prototype stair consists of a mid-level landing and two parallel flights running in opposite directions from the landing to the upper and lower floors. These components are convenient as they can be assembled in-situ using bolted or welded connections at the floor and landing locations. In addition, the presence of handrails on the stair is optional pending the position of the stair relative to other architectural features. The finite element models of the stairs are implemented in *LS-DYNA* as a detailed three-dimensional representation, which explicitly incorporate all the stair components and connections. As summarized in Table 1, different components or connections fabricated using steel with distinct sectional or material properties (e.g., thickness, steel designation) are considered as different parts in the model. Interested readers are referred to [10] for additional details regarding the prototype stair specimen.

Due to the paucity in material test data, these numerical simulations employ the expected (most probable) steel strengths, which are estimated by scaling the corresponding nominal (specified minimum) steel strengths. The scale factors, referred to as expected yield stress ratio R_y or tensile strength ratio R_t in current design provisions [17], are determined based on statistical survey of a large set of material properties [18]. The reported nominal strengths of steel used in the prototype stair model and the corresponding scale factors are summarized in Table 2.

In the proposed model, material nonlinearity is considered assuming elasto-plastic behavior of the steel materials, whereas geometric nonlinearities are accounted for through small-strain large-displacement element formulations. To prevent unrealistic nodal and element penetrations, contact interfaces are implemented wherever potential contact between adjacent components may occur (e.g., surface-to-surface contact for connection plates bearing against the boundary or the other plate). The static coefficient of friction between steel-to-steel contact surfaces is taken as 0.5 in this numerical study. Additional modeling details of individual components (e.g., flights, landing) and connections (e.g., flight-to-landing and flight-to-building connections), the material models, and the boundary conditions are discussed in subsequent sections.

2.1. Stair components

The flight stringers are fabricated using ASTM A36 plate, while the treads and risers are made of ASTM A786 checkered plate (Fig. 2a). All parts of the flights are modeled using four-node fully integrated shell elements (element type 16 in *LS-DYNA*). A refined mesh region with shell element edge lengths ranging from 12.7 mm (0.5 in.) to 25.4 mm (1 in.) is used at both ends of the flight, since large strain and stress gradients are expected in such regions, while the remaining region employs a coarser mesh with a typical element edge length of approximately 50.8 mm (2 in.) to reduce the computational costs. Cyclic plasticity material models (material type 125 in *LS-DYNA*) are used to model the inelastic stress-strain response of steel in the refined-mesh regions (two ends of the flight), while elastic materials are used in the coarse-mesh regions (mid-span). Simulation results (not shown herein for brevity) confirm that the stress level at the flight mid-span regions attains only about 30% of the yield strength at the ultimate loading state (2.5% interstory drift), therefore justifying the use of elastic materials in these regions.

The landing posts and joists are all constructed using ASTM A36 steel (Fig. 2b). Similar to the flight treads and risers, the landing deck is made of ASTM A786 checkered plate. The landing posts are each connected to a joist using two 16 mm diameter ASTM A307 hex head bolts at the top and bolted to steel members at the bottom. The entire landing is modeled using four-node fully integrated shell elements and cyclic plasticity material models. Comparable to those of the flight refined mesh regions, the edge lengths of the landing shell elements range from 12.7 mm (0.5 in.) to 25.4 mm (1 in.).

2.2. Connections

The flights are attached to the building floors at one end and the landing joist at the other end using ASTM A36 plates or angles. It is noted that connection details differ significantly depending on their location on the stair and the boundary details of the supporting structure. For example, Fig. 3a and b present the flight-to-steel member connections of the prototype stair, in which the connection plate and the angle are both bolted to the steel boundary members using two ASTM A325 tension control bolts per connection. As such, surface-to-surface contact is associated with elements on the contact interface to account for the bearing effect of the boundary. All connection plates or angles are shop-welded to the flight stringers using vertical fillet welds at the two ends of the plate or angle.

These connections are modeled using four-node fully integrated shell elements and cyclic plasticity material models. Since large inelastic deformations with complex stress-strain behavior are expected to concentrate at the connections during the lateral loading, the connections are modeled using a refined mesh with a typical shell element edge length of 12.7 mm (0.5 in.). The welds are represented using penalty-based tie contact that rigidly constrains all translational and