Seismic Performance of Scissor Stairs with Fixed-Free Connections

Introduction: Traditional stair construction, in which stair flights are rigidly connected to the structure at both ends ("fixed-fixed" connections), has been shown to cause damage to stairs and surrounding structural members during earthquakes due to stairs being stretched and compressed due to the relative displacement between a building's floors[1]. (See Figure 1.) In response to this, alternative designs ("fixed-free" connections) have been developed[2] that permit stairs to accommodate the relative deformation between stories by detaching the stair at one of the floors. Recent tests[2] have confirmed that fixed-free connections have the potential to eliminate damage due to seismic forces being distributed to stairs, but further testing is needed to understand these novel designs. Scissor stairs, a common configuration in which the stair turns back on itself at a mid-story landing, have not yet been tested in conjunction with fixed-free connections.

Stairs have been shown to affect a structure's seismic response[3], so it is essential to investigate scissor stairs with fixed-free connections not only in isolation but also interacting dynamically with a building. One concern is that releasing degrees of freedom for fixed-free connections may cause a whiplash effect due to the stair's mass being less constrained, damaging nearby building components. Additionally, this whiplash effect may cause undesirable torsion in the building. Therefore, a key challenge in designing fixed-free stairs is to remove enough restraints to permit some movement while preventing completely free oscillation.

I propose to observe and quantify the dynamic characteristics fixed-free scissor stairs and their effect on the lateral response of buildings. Three variations of fixed-free connections will be considered: 1) removing all connections from the lower end of the stairs so that it may slide freely on its landing, 2) use slotted connections to allow some movement while restraining most movement, and 3) using a sliding hanger connection to allow translation in all three dimensions without leaving the stair completely unattached.

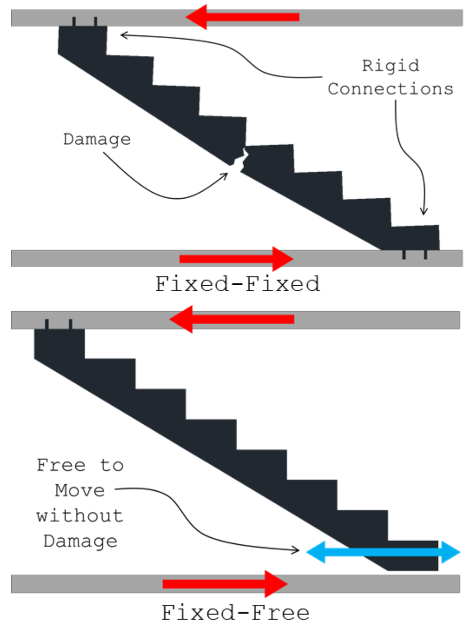

Figure 1: Fixed-fixed response vs. fixed-free response

Hypothesis: Fixed-free stairs will prevent damage that traditionally constructed stairs would otherwise suffer by allowing relative movement between stairs and floors and dissipating energy through friction.

Research Goal 1: Develop Models for Stairs with Fixed and Free Connections

I will model four scissor stair configurations: three with fixed-free connections and a control case with traditional, rigid connections. Because building prototypes and performing dynamic testing is typically cost-prohibitive, I will develop finite element models of the stairs and their connections using the finite element program LS-DYNA. An essential feature of LS-DYNA is its ability to model friction and the interaction between components that come into contact with one another[4]. The models will be subjected to cyclic and dynamic loading protocols to identify the force-deformation behavior of the stair system under earthquake loading.

Research Goal 2: Model Scissor Stairs in Structures

Using the methodology described by Wang et al. (2015)[5], I will represent fixed-free stairs in structures by developing a system of nonlinear springs using the force-deformation relationships found in Goal 1, which will be then integrated into full-building structural models to observe the effect of fixed-free stairs on the seismic response of buildings. For this task, I will use the structural finite element framework OpenSeesPy, which is more appropriate for modelling an entire building. In order to evaluate the effects of fixed-free stair connections, I will subject the models to dynamic loading using a variety of ground motions, then compare member forces and nodal displacements between models without stairs, with traditional stair connections, and with fixed-free stair connections.

Research Goal 3: Improve Full-Building Models by Comparing to Shake Table Test

Working under Professor Keri Ryan at the University of Nevada, Reno, I will participate in the shake table testing of a full-size, 10-story timber building at the NSF's National Hazards Engineering Research Infrastructure (NHERI) facility at UC San Diego in 2021[6]. Because this structure will include scissor stairs with various types of fixed-free connections, this will be an unprecedented opportunity to gather physical data showing the effects of stair-structure interaction. Using this data, I will develop a model of the building including the stairs using OpenSeesPy, which I will validate and calibrate with data from the shake table test. Discoveries from this test will allow me to improve the stair-structure models developed for Goal 2.

<u>Intellectual Merit</u>: Although prior research efforts have investigated the performance of fixed-free connections[2] and the interaction between scissor stairs and structural systems[5], no study has yet addressed coupling the two. Previous tests have demonstrated the potential of fixed-free connections to mitigate damage in stairs[2] sufficiently to warrant further investigation. Accurately characterizing the nonlinear force-deformation relationship of scissor stairs with fixed-free connections will facilitate future research into the seismic response of buildings. Furthermore, developing a nonlinear spring model in Goal 2 will be an important step in helping practicing engineers integrate the results of this research into design practice.

This research will also advance the quality of computational analysis in structural engineering. To my knowledge, I will be the first student at the UNR to extensively use OpenSeesPy, an adaptation of the finite element framework OpenSees for Python. Python has many data science libraries that will improve analysis of data from shake table tests and computational models. Linking Python and OpenSees will improve the quality of structural research by facilitating pre- and post-processing of data from tests and simulations.

<u>Broader Impacts</u>: Failure to account for differential movement between floors has led to stairs collapsing in the recent Wenchuan and Christchurch earthquakes[2]. Fixed-free connections can prevent similar collapses in the future, but first their effects on building response need to be considered before this life-saving technology can be fully implemented. Since stairs are the primary means of egress from a building during a catastrophic event, protecting stairs from collapse during seismic events is an essential task for preventing loss of life. Furthermore, better modelling of stair-structure interaction will ensure safer design and reduce damage, which will in turn facilitate rapid recovery after disasters by reducing building downtime and preventing economic losses.

In order to promote the use of safer stair systems, I will disseminate my findings through publications in structural engineering journals, the NHERI TallWood outreach webpage, and through seminars hosted by UNR's Earthquake Engineering Research Institute chapter. The NHERI TallWood project will give me opportunities to work closely with industry collaborators to further develop and promote fixed-free connections. I will also present a simplified version of my research to K-12 classrooms to foster youth interest in earthquake research.

References:

[1] D. Bull, (2011). *Canterbury Earthquakes Royal Commission*.
[2] C. Black, et al., (2020). *17th World Conference on Earthquake Engineering*.
[3] J. Zhu, et al., (2011). *Applied Mechanics and Materials*.
[4] https://www.lstc.com/products/ls-dyna
[5] X. Wang, et al., (2015). *Earthquake Engineering & Structural Dynamics*.
[6] K. Ryan, et al., (2020). *Colorado School of Mines*.