VALIDATION OF OPENFRESCO-BASED THERMOMECHANICAL HYBRID SIMULATION TO ADDRESS AN EARTHQUAKE-FIRE COUPLED PROBLEM – COUPLED PROBLEMS 2015

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Abstract. A new hybrid simulation platform for addressing thermomechanical coupled problems has been introduced in OpenFresco. This middleware resides between a numerical substructure (NS) and a physical substructure (PS) in a hybrid simulation and provides the means of communicating between the two. Whereas previously, this communication was restricted to mechanical loads, the new OpenFresco thermomechanical hybrid simulation (TMHS) capability additionally provides thermal degrees of freedom and temperature loads in the hybrid model. TMHS was implemented at the ETH Zürich IBK Structural Testing Laboratory. It provides a platform for addressing mechanical-fire coupled problems, and in particular, earthquake-fire problems.

The test presented herein demonstrates the capability of TMHS to simulate structural response to multi-hazard scenarios. The hybrid model consists of two elements. The NS is modeled in OpenSees. The PS is enclosed in a furnace placed in a universal testing machine. The hybrid model is first exposed to a ground motion excitation, applied mechanically by the universal testing machine, followed by a fire load specified by a fire cure and applied by the furnace. After completion of the fire loading and some cooling, a ground motion aftershock is applied to the hybrid model. The entire loading sequence is fully automated, so no user interaction is necessary except to open the doors of the furnace for the cooling phase. Demonstrating this successful investigation of the earthquake-fire coupled problem opens the possibilities for future investigations with more complex models and larger-scale tests.

1 INTRODUCTION

Knowledge about the behavior of structures in fire is severely limited by a lack of adequate testing of complete structural systems. Due to the need for expensive and highly specialized facilities to perform such tests, only a few full-scale tests [e.g. 1,2] or large-scale tests [e.g. 3,4,5] have been performed. Instead, the majority of our knowledge about structural performance in fire is the result of single-component tests [e.g. 6,7,8,9,10,11,12], exposed to standard fire curves. These fire curves do not represent real fires [13], and single-component test do not provide information about the interactions that occur between structural members in a full structure [14].

Structural fire design relies on prescriptive codes which are based on material behavior at elevated temperatures, observed in component tests: thus, the risk of structural system damage or collapse is not evaluated directly. There is great interest to adopt performance-based design approaches for fire [15]. However, high costs and access to sophisticated facilities will continue to impede extensive large-scale testing. The ability to develop performance-based fire design practices will rely on improved testing methods that assess global structural behavior, use of more realistic fire loads that include the post-fire cooling phase [16], and studies of the post-earthquake fire scenario, which is a common multi-hazard occurrence but is not addressed in the state-of-the-art design practices [17]. Hybrid simulation [18], which partitions a structure into numerical and physical substructures (NS and PS), and evaluates response of the combined hybrid model to some external excitation, was designed predominately to evaluate seismic loads. With its flexibility to accommodate different NS and PS configurations, ease of testing multi-hazard scenarios, including safely testing to the point of structural collapse, it is the ideal tool to improve our understanding of structural response in a variety of fire and combined earthquake-fire scenarios.

The thermomechanical hybrid simulation (TMHS) method has been implemented in the Open-source Framework for Experimental Setup and Control (OpenFresco) [19] hybrid simulation software framework, and verified and validated using a small-scale model in an electric furnace at the Swiss Federal Institute of Technology (ETH), Zürich [20].

A TMHS earthquake-fire-earthquake test of a structure exposed to an earthquake, followed by a fire curve, partial cooling, and then an earthquake aftershock is presented herein as a demonstration of the capabilities of this method for simulating multi-hazard scenarios.

2 BACKGROUND INFORMATION

The hybrid simulation testing method provides an opportunity to perform large-scale, coupled mechanical and fire tests, without the need for highly specialized laboratory facilities. It was originally developed [21,22,23] for determining the response of a structure to dynamic excitations, especially seismic. The portion of the prototype structure whose behavior is well-understood is modeled as the NS using standard finite elements, while the portion of the structure whose behavior is highly nonlinear or not well-understood is modeled as the PS using experimental elements. These experimental elements interface with physical specimens in the laboratory through laboratory test setups. The NS and PS interact throughout the simulation via computer control software and the specimen actuation system, which enforce consistent boundary conditions at the interface between the substructures, as the coupled numerical-physical system responds to an excitation.

The structural response of the hybrid model to thermomechanical loads over the time domain of interest is described by the following differential equations (Equation 1).

$$
\begin{bmatrix}
M_{11}^{NN} & 0 & \vdots & 0 & 0 \\
0 & M_{11}^{PP} & \vdots & 0 & 0 \\
\cdots & \cdots & \cdot & \cdots & \cdots \\
0 & 0 & \vdots & 0 & 0 \\
0 & 0 & \vdots & 0 & 0
\end{bmatrix}
\begin{Bmatrix}
\ddot{u}^N \\ \ddot{u}^P \\ \cdots \\ \ddot{\theta}^N \\ \ddot{\theta}^P
\end{Bmatrix}
+
\begin{bmatrix}
C_{11}^{NN} & C_{11}^{NP} & \vdots & 0 & 0 \\
C_{11}^{PN} & C_{11}^{PP} & \vdots & 0 & 0 \\
\cdots & \cdots & \cdot & \cdots & \cdots \\
C_{21}^{NN} & C_{21}^{NP} & \vdots & C_{22}^{NN} & C_{22}^{NP} \\
C_{21}^{PN} & C_{21}^{PP} & \vdots & C_{22}^{PN} & C_{22}^{PP}
\end{bmatrix}
\begin{Bmatrix}
\dot{u}^N \\ \dot{u}^P \\ \cdots \\ \dot{\theta}^N \\ \dot{\theta}^P
\end{Bmatrix}
+
\begin{bmatrix}
K_{11}^{NN} & K_{11}^{NP} & \vdots & K_{12}^{NN} & K_{12}^{NP} \\
K_{11}^{PN} & K_{11}^{PP} & \vdots & K_{12}^{PN} & K_{12}^{PP} \\
\cdots & \cdots & \cdot & \cdots & \cdots \\
K_{21}^{NN} & K_{21}^{NP} & \vdots & K_{22}^{NN} & K_{22}^{NP} \\
K_{21}^{PN} & K_{21}^{PP} & \vdots & K_{22}^{PN} & K_{22}^{PP}
\end{bmatrix}
\begin{Bmatrix}
u^N \\ u^P \\ \cdots \\ \theta^N \\ \theta^P
\end{Bmatrix}
=
\begin{Bmatrix}
F_u^N(t) \\ F_u^P(t) \\ \cdots \\ F_\theta^N(t) \\ F_\theta^P(t)
\end{Bmatrix}
\quad (1)
$$

N in the superscript refers to the NS and P in the superscript refers to the PS. The variables u, $\dot{u}$, and $\ddot{u}$ are the mechanical displacement, velocity, and acceleration, respectively. θ, and $\dot{\theta}$ are the temperature and rate of temperature change, respectively. M_{11} is the mass matrix. C_{11} is the mechanical damping matrix. C_{21} is the heat generation due to strain rate, which is important for micro-scale applications but is neglected for large-scale civil structural tests. C_{22} is the thermal capacity matrix. K_{11} is the mechanical stiffness matrix. K_{12} represents the internal forces due to restrained thermal deformations. K_{21} represents the thermal load changes due to mechanical displacements. K_{22} is the thermal conductivity matrix. $F_u(t)$ are the time-dependent mechanical external forces. $F_\theta(t)$ are the time-dependent thermal fluxes.

Fully coupled physics is defined as the situation when thermal behavior affects the mechanical behavior and vice versa. For most problems, full coupling only involves the K_{12} off-diagonal term. K_{21} is important in cases when the specimen undergoes large deformations in a compartment with a non-uniform temperature, such that the mechanical behavior of the specimen changes its thermal exposure (particularly when the structural deformations result in new ventilation, e.g. when a window breaks or integrity of a fire wall is lost).

The substructures are mechanically fully coupled when the displacements are sent from the NS to the PS and interface forces are measured and returned from the PS back to the NS (displacement control). The feedback restoring forces are used to compute the displacements in the next time step, so the displacement sequences applied to the PS are not known a-priori. The substructures are fully coupled thermally when temperatures are sent from the NS to the PS and thermal fluxes are measured and returned from the PS back to the NS (temperature control). The substructures are fully coupled thermomechanically when they are fully coupled mechanically and thermally. The substructures are partially coupled thermomechanically when the substructures are fully coupled mechanically or thermally but not both.

The first application of hybrid simulation to investigate structural response in fire was performed by Mostafaei [24,25]. A standard fire test of a single column PS was combined with a NS of the remainder of the structure to enable examination of the behavior of the whole structure exposed to both mechanical and fire loads. However, this implementation involved human interaction for data transfer between the numerical and physical substructures. TMHS advances the state-of-the-art by providing computer controlled interaction between the NS and PS. This automated infrastructure is critical for working with complicated models, eliminating the possibility of human error in data transfer, maintaining synchronization of the mechanical and thermal loading patterns in the event of a hardware delay in the laboratory, and enabling real-time testing capabilities.

3   TMHS EARTHQUAKE-FIRE-EARTHQUAKE SIMULATION

3.1 TMHS Framework

TMHS uses the Open System for Earthquake Engineering Simulation [26] software framework for modeling the NS. The OpenFresco hybrid simulation software framework provides the communication link between the NS and the PS, including the degree of freedom (DOF) transformations between the NS and the test setup in the laboratory and the interface with the test setup control system. Because OpenSees and OpenFresco were both originally developed for purely mechanical problems, the frameworks were extended to include the temperature DOFs at the nodes of the hybrid model [20]. The DOF transformation and experimental control for the thermal problem are both new additions to OpenFresco.

The earthquake-fire-earthquake TMHS presented here was done using a hybrid model with a partial coupling of the physics and a partial coupling of the substructures. Because OpenSees solves purely mechanical problems, the NS is not exposed to thermal loads. Developments for thermal capabilities in OpenSees are underway by researchers at Edinburgh [27,28]. Displacement control is used, meaning that the hydraulic actuator applies displacements to the PS and measures restoring forces. The temperatures are controlled on the PS, but the thermal fluxes are not measured and returned back to the NS. This constitutes a partial coupling of the substructures.

In the earthquake-fire-earthquake test, the equation of motion is solved in each time step using a hybrid simulation specific (but mechanical-only) Newmark Implicit integrator with an increment reduction factor of 0.4 and a fixed number of 4 iterations per time step [29]. The fixed number of iterations per time step is important for real-time hybrid simulation such that each simulation time step is applied in the same amount of clock time. The number of iterations necessary to achieve the required tolerance in each simulation time step is preselected based on the performance of the hybrid test in full-simulation (PS modeled as another NS on a separate processor) mode.

3.2 Experimental Design

The earthquake-fire-earthquake test is conducted on a simple single DOF hybrid model. A single beam element NS is implemented in OpenSees (A) and a single truss element PS is modeled physically (B), as shown in Figure 1a. The fundamental vibration period of the hybrid model was set at 1 s and instantiated by calculating the necessary mass and assigning this mass entirely to the NS. A 5% mass proportional Rayleigh damping is used. The PS is a Grade S355 structural steel RHS 120-60-3.6 dogbone-shaped specimen (the narrow portion of the dogbone shape is 75 mm long, 10 mm wide, and 3.6 mm thick), tested in a combined Zwick 1484 Universal Testing Machine (UTM), which applies axial displacements and measures reaction forces, and a Könn STE-12 HR/350' (0.1 m radius x 0.5 m tall) electrical furnace, which encapsulates the specimen and controls the temperature at specimen mid-height (Figure 1b). Though the TMHS framework is designed to enable real-time testing, the low heating power of the Könn furnace cannot achieve real-time temperature loadings. An extensometer measures the strain of the physical specimen directly. The length, L, in Figure 1a, is 40 mm to match the gage length of the extensometer probes. Three thermocouples measure temperature on the surface of the specimen. An Indel CPU board stand-alone master

(SAM) is used as the digital signal processor (DSP), responsible for generating displacement and temperature command signals and receiving feedbacks from both the UTM and furnace.
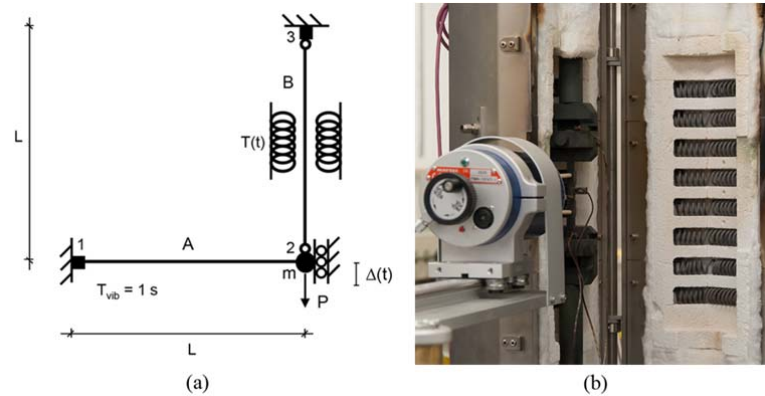

Figure 1: (a) Hybrid model; (b) Physical specimen in the furnace

In this earthquake-fire-earthquake test, PS response was maintained in the elastic range because this test was part of a series of proof tests and the specimen was reused many times. Furthermore, the UTM is configured for tensile loads only, so compression of the PS had to be prevented. Performing the test in displacement control in this scenario requires careful design and coordination of the mechanical and thermal load patterns. As the specimen heats in a displacement controlled environment, its expansion has the effect of reducing the restoring force. The mechanical load pattern must counteract this behavior to maintain some tension on the specimen at all times, but not too much tension such that the specimen yields.

With these requirements in mind, the earthquake-fire-earthquake test was performed in the following way. Initially, a small force ramp of 5 kN was applied to the single DOF in the hybrid model over 30 simulation seconds and 120 steps. Then the 1940 El Centro NS ground motion was applied using a very small scaling factor (0.0005) to avoid yielding the PS. This ground motion record has 1600, 0.02 s long steps: thus, it took 32 simulation seconds. Next, another small force ramp of 5 kN was applied to the single DOF in the hybrid model. Simultaneously, the fire curve was commanded to the experimental element in the hybrid model (and thus sent to the PS). This was performed over 30 simulation seconds and 120 steps. The fire curve was the international standard ISO 834 temperature-time curve, scaled to reach 200 deg C at 30 s, and defined in the Eurocode 1 Part 1-2 [30] as:

$$\Theta_g = 20 + 345\log_{10}(8t + 1) \tag{2}$$

where Θ_g is temperature (˚C) in the fire compartment and t is time (min). After the peak of the fire curve was attained, the furnace was turned off and its doors were opened, with the intent to apply linear time-temperature cooling pattern over 90 simulation seconds. A negative 5 kN force ramp was applied simultaneously to unload the specimen and avoid yielding it as it cools and contracts. Finally, the 1940 El Centro NS ground motion scaled with the same scale factor of 0.0005 was applied to the hybrid model with the furnace door open to represent an aftershock striking a partly cooled structure.

3.3 Results

The displacement command history and temperature command history for the earthquake-fire-earthquake test are shown in Figure 2.
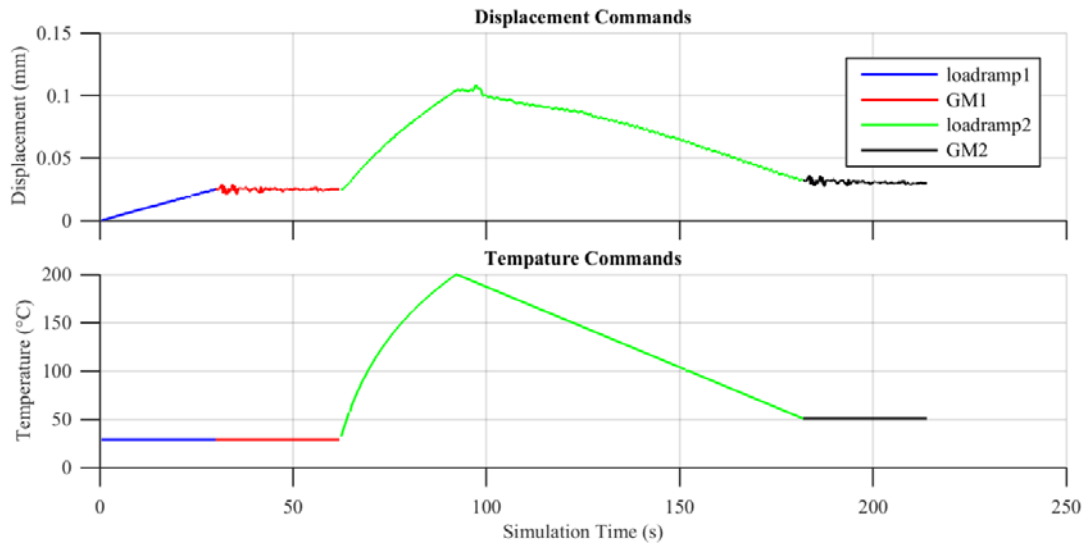

Figure 2: Displacement and temperature commands

The force feedback history and temperature feedback history are shown in Figure 3. The control of the temperature at the start of the cooling phase has a small error. The cooling phase should follow a linear decreasing time-temperature ramp. However, when the furnace doors were opened, the temperature dropped quickly. OpenFresco temperature error tolerance was set at 5˚C, but the temperature dropped too fast below the tolerance range. By temporarily allowing a higher temperature error tolerance, the discrepancy was resolved, and the remainder of the cooling ramp was performed as planned.

The displacement control errors and temperature control errors are shown in Figure 4. The displacement control errors are all on the order of 10^{-3} mm. The temperature control errors are generally within +/-5˚C, except for the error when the furnace doors were opened. At the end of the test, the temperature continued to drop as the aftershock earthquake was applied. This is a realistic scenario for continued cooling while an earthquake is applied to a partly cooled structure.
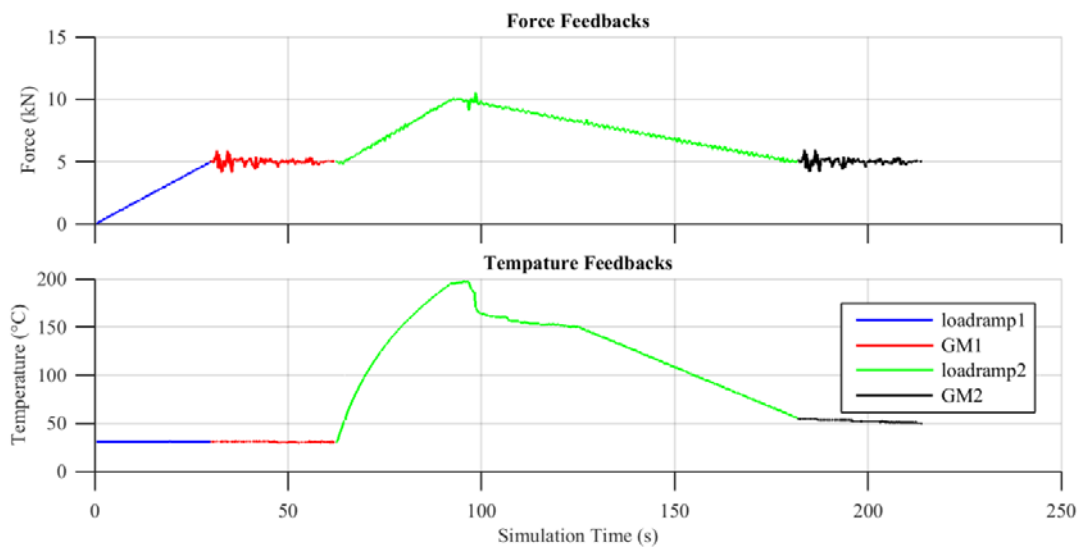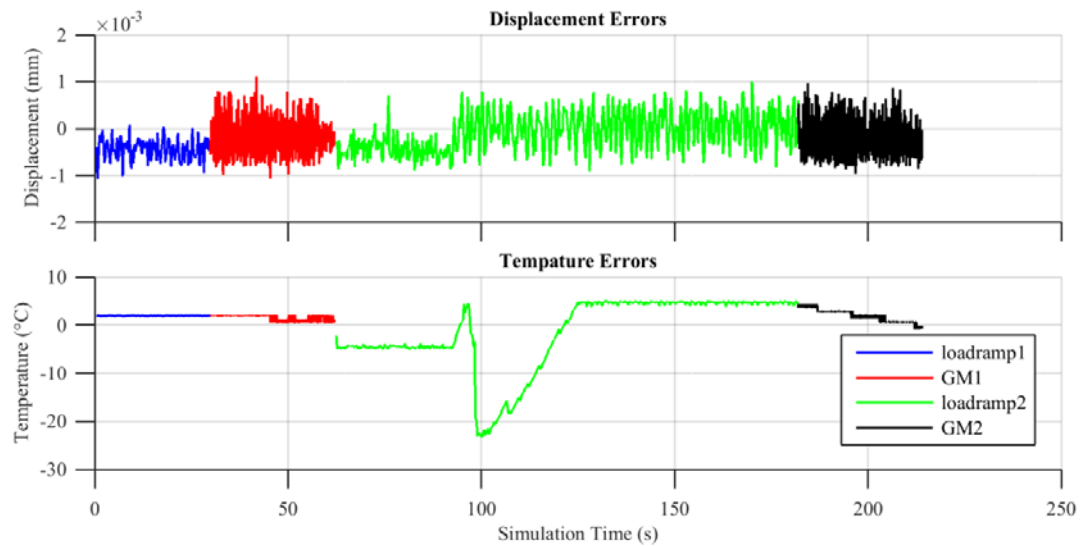
Figure 3: Force and temperature feedbacks

Figure 4: Displacement and temperature control errors

The force-displacement hysteresis for the single DOF of the hybrid model is shown in Figure 5. The forces are the sum of the restoring forces from the NS and PS. The specimen remains linear for the entirety of the test. This is confirmed by the same slope for the first load ramp (load ramp 1), the initial earthquake (GM1), and the final earthquake (GM2). The green line (load ramp 2) plots both the combined effects of the increasing load ramp (+5 kN) and the thermal load (fire curve), followed by the simultaneous decreasing load ramp (-5 kN) and cooling phase. The lower slope of this green line is the result of the specimen resistance dropping as it heats and expands (and the reverse during unloading and cooling).
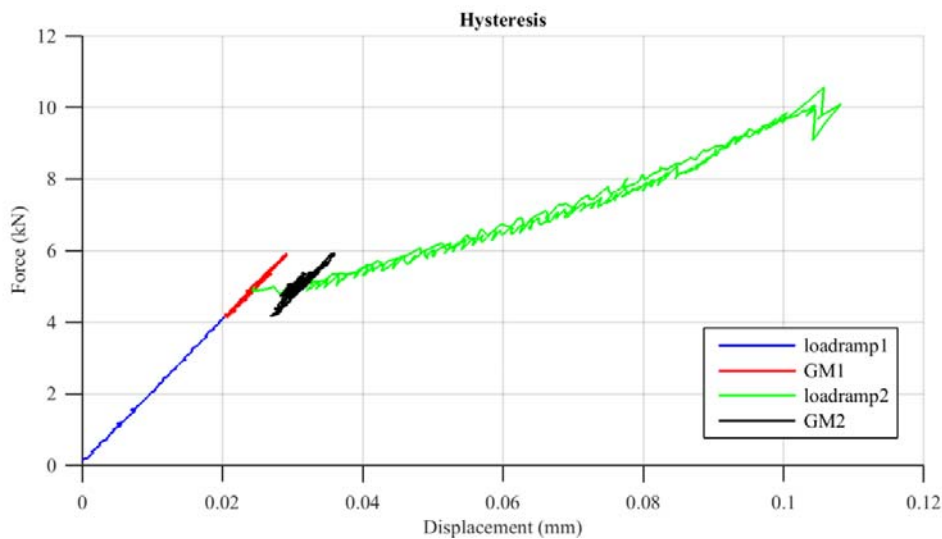
Figure 5: Hybrid model force-displacement response

4   CONCLUSIONS

The lack of knowledge about the behavior of entire structures in fire scenarios is a result of a lack of adequate testing. Very few full-scale structural fire tests have been performed due to the need for highly specialized facilities and high costs. Instead, tests are largely performed on single structural components, exposed to standard fire curves. Fire ratings are the outcome of such tests, which feed prescriptive fire design codes.

As in seismic design, fire design is moving towards performance-based standards. By designing for specific performance levels in hazard scenarios, the overall behavior of the structure will be considered from the outset of the design process. The risk to structures in fire scenarios will be known and quantifiable.

Development of performance-based fire design hinges on the development of new testing methods that can assess the global behavior of structures in fire. The thermomechanical hybrid simulation framework addresses these needs. A TMHS proof test, presented in this paper, demonstrated the capabilities for testing multi-hazard scenarios. The response of a hybrid model to an earthquake, followed by a fire, a partial cooling phase, and an aftershock earthquake was successfully simulated.

There are many opportunities for future work. The NS portion of the hybrid model used in the proof test was "cold". By interfacing OpenFresco with finite element software that is specifically developed for thermomechanical hybrid simulation, such as SAFIR [31], more powerful numerical models can be instantiated and full coupling of the physics can be enforced. By measuring thermal flux feedback from the PS, full coupling of the substructures can be implemented. The low heater power of the Könn furnace and its poor controller were major impediments to the TMHS tests. With a more powerful furnace or other powerful heating elements, real-time TMHS is possible. The developments in OpenFresco presented herein support such real-time simulations.

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11 ACKNOWLEDGMENTS

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