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HYBRID FIRE TESTING OF A SINGLE DEGREE-OF-FREEDOM LINEAR SYSTEM

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ABSTRACT

As the structural engineering industry transitions towards performance based design methods, a better understanding of the performance of structures as full systems, especially under extreme loading conditions like fire, becomes a must. Full scale testing will provide such information, however, at an unrealistic cost. Hybrid Fire Testing (HFT) is inspired from sub-structuring method, which provides the insight through testing individual members exposed to elevated temperatures, while simultaneously accounting for the effect of the surrounding structure, which is numerically modelled aside. The tested member and the numerically represented surrounding must communicate during the entire test. This communication framework is a key component for a successful HFT. However, there is lack of availability of generic frameworks that enable the use of different software and hardware configurations. This paper presents the development of such generic communication framework. First, a validation of the communication framework was done in a virtual environment, where both the tested member and the surrounding are numerically modelled separately. Next, a hybrid fire test was performed on a single degree-of-freedom linear system.

Keywords: Hybrid fire testing, fire tests, substructures, communication framework

1 INTRODUCTION

There is a lack of understanding of how structures, as whole systems, perform under realistic fires. A better understanding of the problem will support the development of performance-based standards and tools that explicitly consider realistic fire effects for both the design of new buildings and the assessment and retrofit of existing ones. The Hybrid Fire Testing (HFT) method, through sub-structuring, assumes testing individual members/components (referred to as physical substructure (PS)), while simultaneously accounting for the action of the surrounding structure (referred to as numerical substructure (NS)) which is computationally modelled aside. Thus, HFT allows, through testing individual members, the prediction of the global behaviour of whole structural systems. To date, only few HFT performed on full size structures are found in the literature [1-4]. Small scale HFT are presented in [5,6] and virtual hybrid fire tests (VHFT) (the PS and NS are represented numerically) are presented in [7,8] to validate new methods. These studies have been performed considering standard fire curves (e.g., [9]), while more researchers are currently focused on studying the behaviour of structures exposed to realistic fire scenarios [10-11].

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A recent study performed on a prototype building exposed to two simulated realistic fire scenarios [12] showed how much the simulation of individual members could be different than the simulation of the complete structural system in terms of behaviour. Analysis of individual members simulated individual member test behaviour while analysis of the full structure simulated the full-scale testing of the structure as a system. The study highlighted that in some cases, individual members survived the fire, while failure occurred when the complete structural system was modelled. Thus, difference between the individual member testing and full-scale testing can be crucial in terms of safety. HFT is a potential solution that insures the proper accounting of the surrounding system on the individual member behaviour.

To perform a successful HFT, several key components are crucial [13], one of them is the framework for the experimental setup and control. Most testing facilities develop their own framework, while open-source frameworks such as OpenFresco [14] and UI-Simcor [15] have been successfully used in the seismic field. To perform a HFT using frameworks as OpenFresco or UI-SimCor, some modifications need to be implemented, making them more generic, thus allowing them to integrate with certain finite element software that have the capability to solve structures loaded with both mechanical and fire loads (e.g., SAFIR [16]). The main objective of this paper was to validate the HFT concept through developing a generic communication framework and using it to perform a HFT on a single degree-of-freedom (1-DoF) linear system. Some modifications were implemented so that OpenFresco can communicate with SAFIR. A virtual hybrid fire test (VHFT) was performed on a single degree-of-freedom (1-DoF) linear system in order to test these modifications. The communication proved to be successful and this framework can be used in future HFT where the NS is to be represented in SAFIR or other similar software packages. Following the VHFT, a HFT was performed on the 1-DoF linear structural system. National Instrument’s LabView [17] is used to establish data exchange between the third-party frameworks OpenFresco (OpenSees) / Matlab / SAFIR. This simplified test setup helped validate the HFT methodology presented in [18], and the interface described above.

2 APLICABILITY OF HYBRID FIRE TESTING

It is important to study behaviour of structures exposed to fire conditions in the most similar conditions with reality. In real fires, it has been observed that the fire spreads from one compartment to another, and in order to understand the real behaviour of structures in these specific conditions, real-scale tests are required to validate the fire models and structural models.

Most of the fire tests are performed on individual structural members exposed to standard fires, based on the assumption that the predictions of these tests are overly conservative. A recent study [12] performed on a prototype 10-story moment resisting frame [19] when exposed to 2 design fire scenarios showed that the results from the simulation of the individual members are not conservative compared with the results of the complete structure simulation. The study highlighted that performing fire tests on individual members might not always be a conservatively safe solution. The beam situated in the fire compartment where the fire initiated was considered as a key element of the structure and it was studied in different possible configurations. The following boundary conditions are possible when testing the beam as a standalone member: f-f (fixed-fixed ends), f-th (fixed-fixed ends with free thermal expansions), f-h (fixed-hinged ends), f-r (fixed-rolling supports), s-s (simply supported beam), h-h (hinged-hinged ends).

Fig. 1 shows the evolution in time of the mid-span displacement of the beam when subjected to the mentioned boundary conditions. It is noted that these results come from finite element analysis and not from real tests. In most cases of the standalone member analysis (e.g., "f-f", "h-h" in *Fig. 1*), the mid-span displacements of the beam are higher than in the case when the full structure assembly was analysed ("full-scale S1 and "full-scale S2" represent the two different fire scenarios). Nevertheless, the standard testing simulation did not lead to the failure of the members, while in the case of the full-assembly simulation, the failure of the structural system occurred in both fire scenario cases. The standalone member testing (analysis) does not capture the full effect of the surrounding members during the test. The surrounding assembly starts being exposed to fire since the fire spreads from one compartment to another. The capacity of the member is overestimated if the effect of the surrounding members is neglected. This is a clear example of HFT applicability, it is built on the concept of continually accounting for the whole assembly behaviour while realistically testing a member or sub-assembly.

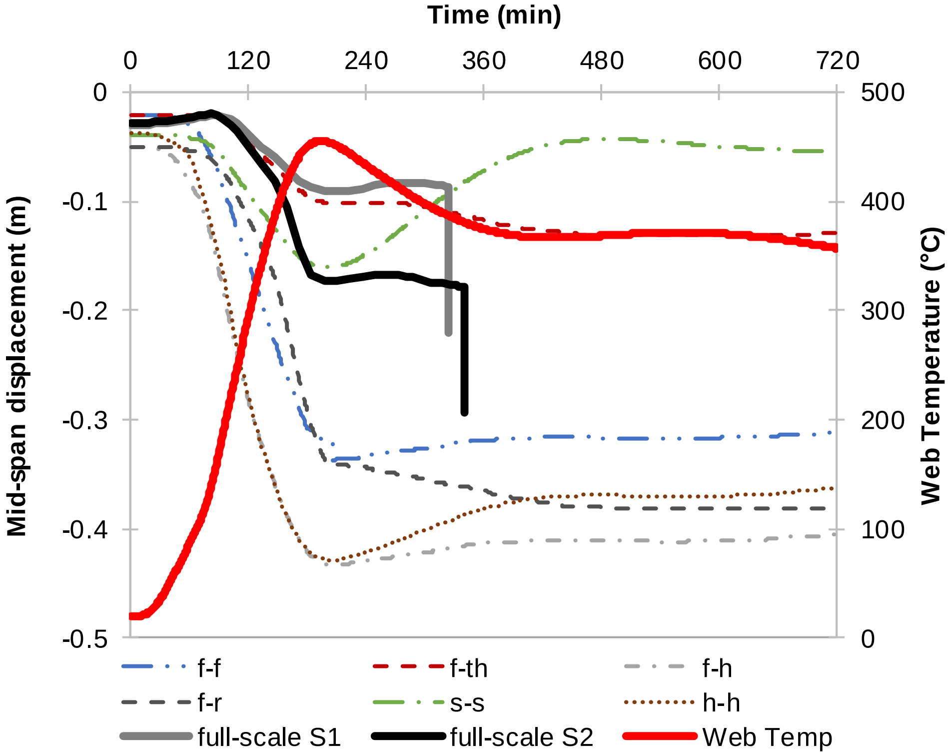

Fig. 1. Mid-span displacement of the beam in different testing configurations

3 HFT ON A SINGLE DEGREE-OF-FREEDOM SYSTEM

As presented in [13], one of the biggest challenges in performing HFT is to ensure a proper communication between the PS and NS. Frameworks for experimental setup and control such as OpenFresco and UI-SIMCOR have been successfully used in seismic hybrid simulations. These frameworks ensure the proper control of the PS, which communicate in real time with the NS during the entire test.

To perform a HFT using frameworks as OpenFresco or UI-SimCor, some modifications are due, making them more generic, thus allowing them to integrate with certain finite element software that have the capability to solve structures loaded with both mechanical and fire loads (e.g., such as SAFIR).

To make the communication between SAFIR and OpenFresco possible, some modifications were implemented in SAFIR and a communication framework was developed in MATLAB. To test this communication interface, first a virtual hybrid fire test VHFT was performed, in which the PS and NS are both modelled numerically. Once the VHFT confirmed the successful continuous communication, a real HFT was performed. The main purpose of the test was to validate the hybrid fire testing methodology presented in [18] and the communication framework mentioned above. The 1-DoF linear system (*Fig. 2*) considered in this example was composed of 2 bars, defined by their stiffness. One of the bars was exposed to elevated temperature, and the thermal expansion induced changes at the interface node 2. For the sake of simplicity, the stiffness of the heated substructure was considered constant during the entire test.

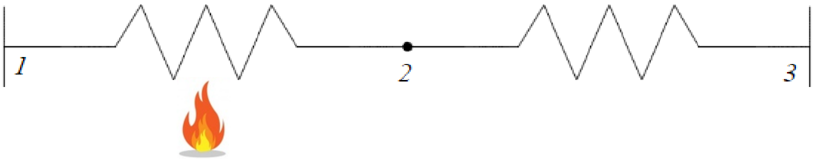

Fig. 2. One degree-of freedom linear system

The main characteristics of simplified 1-DoF linear system considered in this example are the following:

- The stiffness of the substructures: $K_P=11.30$ N/mm (PS) and $K_N=11.30$ N/mm (NS)
- The length of the substructures: $L_P=260$ mm (PS) and $L_N=260$ mm (NS)
- The thermal coefficient of the material is $\alpha=0.00012$ 1/K
- The rate of temperature increase of the heated substructure is taken as $200\ \mathrm{°C/s}$ (the stiffness of the PS is considered constant).

Prior the real HFT, a VHFT was performed and the results are presented in the following section.

3.1 Virtual Hybrid Fire test (VHFT)

Performing a VHFT (PS and NS are both represented numerically, i.e., separately modelled) is generally useful for the purposes of: (i) testing the framework integrating the different analytical software, and (ii) preparing for the real HFT by helping select the proper time step for the simulation in cases for which no analytical formulations are available.

The communication between SAFIR and OpenFresco is possible because of the developed communication framework in Matlab (see *Fig. 3*). In addition, modifications were done in SAFIR's code in order to allow such communication. The HFT methodology presented in [13] was used in this VHFT, and it was implemented inside the communication framework. The advantage of this particular framework is that it allows the communication between experimental setup and control frameworks with a wider range of software packages that have the capabilities to solve structures loaded with both mechanical and fire load (in this case SAFIR). Also, this communication framework is generic, and can be accessed and modified based on the needs of each case study.

In this VHFT example, the heated substructure was modelled in SAFIR, while the cold substructure was modelled in OpenSees [20]. OpenFresco was used to communicate between SAFIR and OpenSees. In a real HFT, OpenFresco will instead communicate between the tested PS and modelled NS in SAFIR.

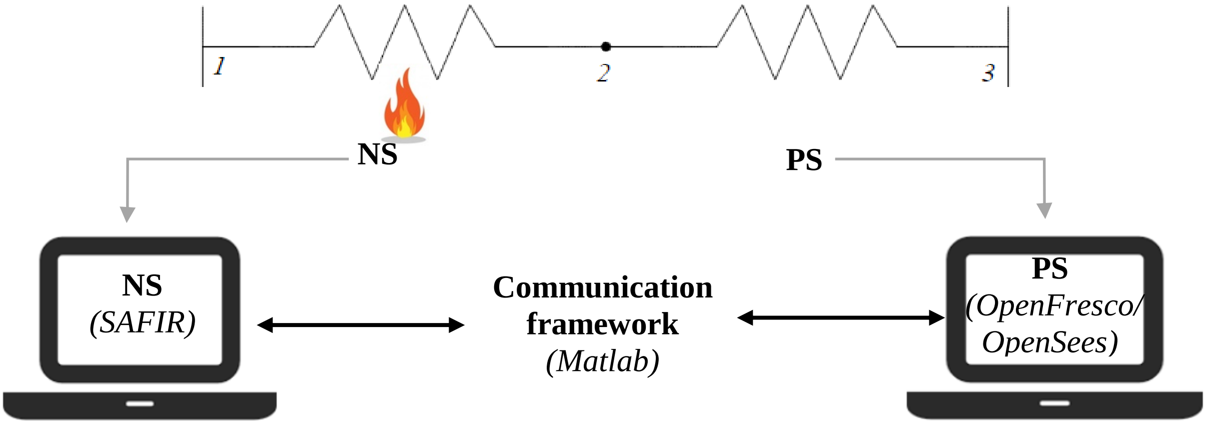

Fig. 3. Communication between OpenFresco / OpenSees and SAFIR during the VHFT

Fig. 4 presents the evolution of the interface force versus the interface displacement of the 1-DoF linear system, i.e., the interface force and displacement of the node 2 (see *Fig. 3*). Each of the graphs presents the solution of the global (whole system) analysis of the 1-DoF linear system (referred to as "Global") along with the solution from the VHFT ("NS" is the interface solution of the NS analysed in SAFIR and "PS" is the interface solution of the PS analysed in OpenSees). The

VHFT solutions are presented for two different considered time steps Δt: $\Delta t=1$ s and $\Delta t=10$ s. The time step refers to the time when the displacement is fixed to a constant value (since a displacement control procedure is used). Once the new solution is computed, it needs to be updated on the PS and NS before running the next step. For this example, *1 s* is the time needed to update these values on the substructures.

This VHFT showed that the interface solution of the PS and NS were the same, meaning that the equilibrium and compatibility were both satisfied. Moreover, the global solution was reproduced successfully by VHFT (the lines on the plot align on top of each other). The heated substructure (NS) needs to expand but the displacement is constant during one-time step (displacement control procedure), therefore, the interface force is increasing. The force increase of the NS during one time step is obvious in this example for a time step equal to 10 s (*Fig. 4 b)*). Once the interface displacement is updated, the reaction force of the NS (heated substructure) is in equilibrium with the reaction force of the PS.

The stiffness values of the PS and NS are required for the calculation process of the updated boundary conditions (displacement of the node 2). However, as the substructures are exposed to elevated temperatures, their mechanical and material properties (which are temperature-dependent) degrade, i.e., the stiffness varies with temperature. In a real HFT the stiffnesses of the PS and NS can be updated every time step or it can be kept constant. If the stiffness is kept constant, then several iterations are required to converge to the correct solution. For this simplified example, the hypothesis that the stiffness is not affected by the elevated temperatures was adopted. Therefore, the stiffness of the PS and NS were kept constant during this entire VHFT and once the displacement was updated at the interface, the correct solution was achieved along with the equilibrium and compatibility (no iterations were required).

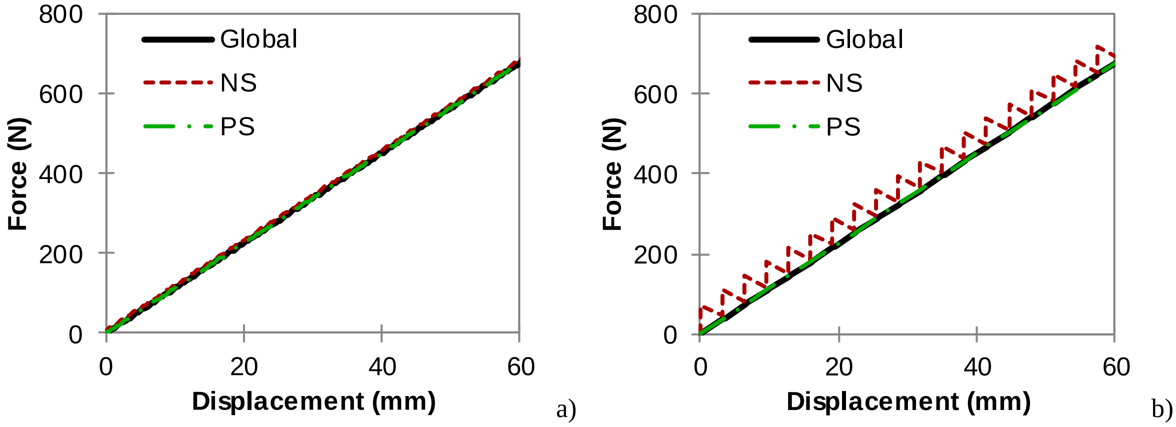

Fig. 4. Interface solution (force versus displacement) for the 1-DoF linear system: a) $\Delta t=1$ s; b) $\Delta t=10$ s

This VHFT's communication framework successfully enabled the communication between SAFIR and OpenFresco / OpenSees. The following section shows how the developed communication framework was implemented in a real HFT performed on a 1-DoF linear system. In general, performing a VHFT prior to conducting a real HFT is beneficial for many reasons. It can be used to properly select the optimum value of the required time step. It can also be helpful in determining the influence of using constant stiffness values (versus updating them every time step) of the PS and NS on the results.

3.2 HFT of a 1-DoF linear system

Following the VHFT, a HFT was performed on the single degree-of-freedom (1-DoF) linear structural system shown in *Fig. 5*. In this setup, the PS and NS were represented by springs. Prior the HFT, the stiffness of the PS was measured and had a value of +11.30 N/mm. The stiffness of the NS was assumed to be equal to the stiffness of the PS. All the characteristics of the system are presented in section 3. Since the objective of this experiment was to test and validate the communication framework, and not necessary the specific structural response to the fire load, the unheated substructure was physically tested (PS) while the heated substructure was modelled (NS) in SAFIR. National Instrument's LabView was used to establish the data exchange between the frameworks PS / OpenFresco / Matlab / SAFIR.

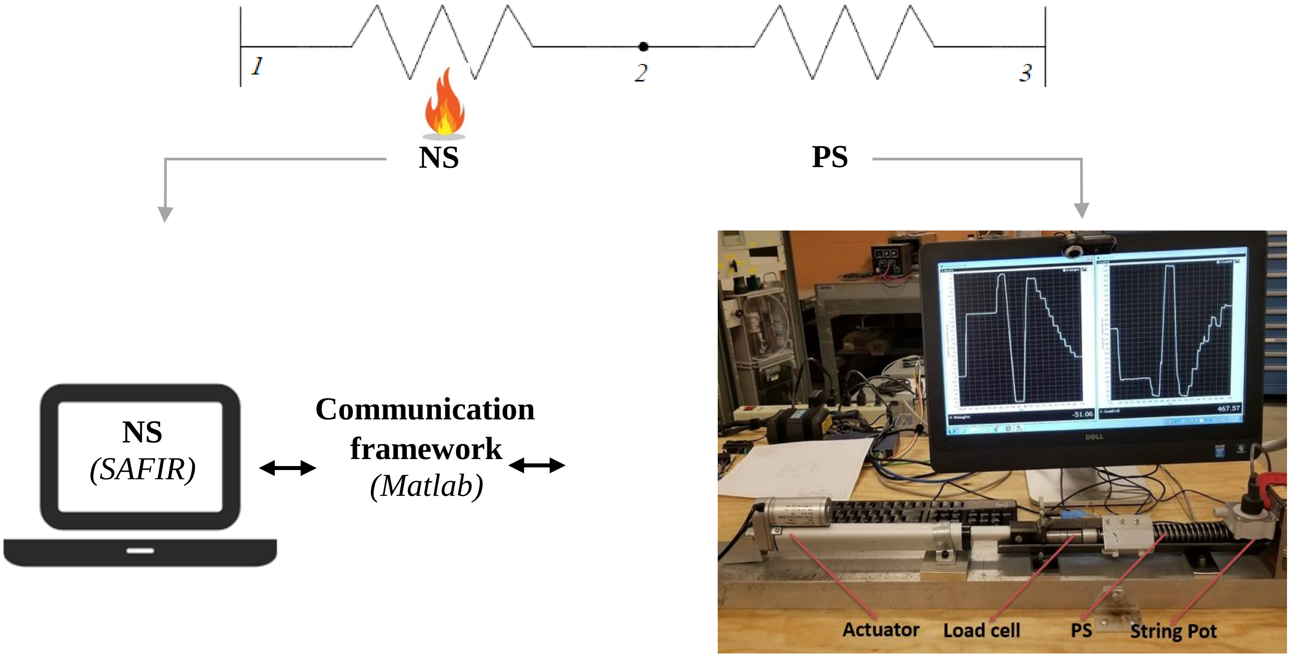

Fig. 5. HFT of the 1-DoF linear system

The test setup is presented in *Fig. 5*. The actuator is imposing the target displacement which is measured by the string pot. The force is measured by the load cell. The properties of the measurement instruments along with the uncertainty of measurements are presented towards the end of this section.

Fig. 6 presents force versus displacement at the interface, i.e., at node 2 (*Fig. 5*), during the HFT. The global solution results from the global numerical analysis of the 1-DoF linear system (referred to as "Global" on the plot) while the results from the HFT are "PS" (the interface solution of the PS) and "NS" (the interface solution of the NS). It is noted that this work is underway, and the results presented in the *Fig. 6* are preliminary results. A time step of 10 *s* was used to update the interface displacement and the time to induce the target displacement was 1 *s*. During one-time step, the displacement is kept constant at the interface and this induces an increase of the reaction force of the heated substructure (NS in this case). Once the displacement is updated, the reaction force of the NS reduces and has the same value as the reaction force of the PS. This shows that the compatibility and the equilibrium are both satisfied in each time step. In order to reduce the spikes of the NS's solution, a shorter time step can be used as presented in the VHFT (see *Fig. 4 a)*). A slight deviation of the HFT solution from the global analytical solution was observed toward the end of the test which could be due to the spring bowing out of plane once it gets compressed.

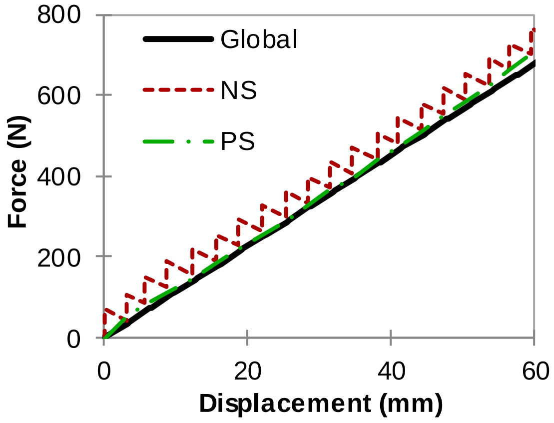

Fig. 6. Force-displacement during HFT of the 1-DoF linear system

This simplified HFT showed successful implementation of the developed communication framework. It is noted that this setup could be reversed where the fire load is applied to the PS instead of the NS. In real HFT applications, the fire would potentially be applied on the tested substructure (PS), as the unheated structure could be numerically modelled with less uncertainty than the heated sub-structure. This framework is also ready to be extended to more complicated systems with multiple DoF (requiring multiple actuators).

Although the work described herein is a proof of concept for the purpose of presenting the successful implementation of the developed communication framework, some details of the measurements are worth mentioning. It is noted that the string pot used was a Celesco SP2-50, with a 1270 mm maximum measuring length. Its combined uncertainty was ±2 %, and the total expanded uncertainty based on coverage factor of two (corresponding to a 95 % confidence interval) was 4 %. The load cell was an OMEGA LCWD-20K, with a 90 kN capacity. Its combined uncertainty was ±10 %, and the total expanded uncertainty was 20 %. The uncertainties for both measurements were calculated based on [21].

4 CONCLUSIONS

There is a lack of understanding of how structures, as whole systems, perform under realistic fires. The Hybrid Fire Testing (HFT) method, through sub-structuring, and testing individual members/components, while simultaneously accounting for the action of the surrounding structure which is computationally modelled aside, has proven to have great potential for solving this problem. However, a main challenge in HFT is the continuous communication between the tested sub-structure and its numerically modelled surroundings. This paper presented the successful implementation of a newly developed communication framework for HFT. It was performed on a single degree-of-freedom linear system, both in a virtual and in a real setup.

DISCLAIMER

Certain commercial software or materials are identified to describe a procedure or concept adequately; such identification is not intended to imply recommendation, endorsement, or implication by the National Institute of Standards and Technology (NIST) that the software or materials are necessarily the best available for the purpose.

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