WORKSHOP HYSIM19: New Frontiers and Innovative Methods for Hybrid Simulation

C. NEW FRONTIERS & APPLICATIONS

- Co-leads: **Oh-Sung Kwon** - Abstract title: Hybrid Simulation Framework, UT-SIM, and its Applications to Structures Subjected to Earthquake or Fire Load

- Co-leads: **Patrick Covi** - Abstract title: Hybrid fire testing of a virtual steel frame

- Recorder: **Barbara Simpson**

- Speaker 1**: Silvio Renard** - Abstract title: An adaptive controller for hybrid fire testing

- Speaker 2**: Elke Mergny** - Abstract title: PI-Control in Hybrid Fire Testing

- Speaker 3: **Reto Grolimund** - Abstract title: A Coupled Experimental and Numerical Framework for the Analysis of Steel Structures Subjected to Fire

- Speaker 4: **Giuseppe Abbiati** - Abstract title: A Real-time Hybrid Fire Simulation algorithm Based on Dynamic Relaxation.

Oh-Sung Kwon – Hybrid Simulation Framework, UT-SIM, and its Applications to Structures Subjected to Earthquake or Fire Load

- Challenges in numerical modelling – structures subjected to fire
- Modelling of fire scenario and heat transfer analysis
- Temperature-dependent material properties
- Vapor pressure increase and concrete spalling

Earthquake Loads

- Static-fire test – typically under constant load, no interaction with the structural system
- Full-scale – most complete and accurate, limitations in scale, expensive

Structural performance assessment via hybrid simulation

- $\cancel{m\ddot{u}(t) + C\dot{u}(t)} + R(u, T) = F$

UT-Sim Framework

General requirements:

- Numerical integration modules
- Communication
- Capability to impose predicted displacements
- Delay compensation

UT-10 Hybrid Simulator

Component/system-level decomposition

- TCP-IP communication to the network
- To run in many other labs outside of University of Toronto
- Ability to test multiple (10) components under axial loading

Applications to Seismic Load

- **5-story BRBF**
- Model only core of BRB; remainder modeled numerically
- High confidence in the numerical model; however, the hybrid simulation did not reflect results
- **5-story CBF**
- Scaled specimens of braces in bottom stories
- **Cast steel link element in EBFs**
- Castconnex – prefabricated elements
- Multi-axial hybrid simulation using shell element testing
- Ongoing
- **Steel yielding connection elements**

Applications to Fire Load

- $R(u, T) = F$, Temperature changes with time
- Modified stiffness method (initial stiffness)

- Neglecting dynamic response due to temperature load
- Measuring “time” component can withstand elevated temperature load
- Impose heat transfer analysis on the numerical model
- Run nonlinear structure analysis
- Send a signal to the actuator controller
- Apply to specimen
- And send back to the nonlinear analysis
- **Example**
- Challenges: stiff specimen and elastic deformation of loading frame – used load cell reading, estimated frame stiffness, estimated specimen deformations
- Potential thermal expansion of supporting elements
- Stability during testing
- Error from increasing temperature over time
- **Test D w/o error compensation**
- While heating, load increases, column started yielding
- No oscillations
- **Test E w/ error compensation**
- Results in oscillations
- Stiffness of loading frame hardens; leading to oscillations
- Could have more sensors to directly measure specimen deformations in column
- **Real-time continuous testing** (rather than ramp and hold)
- Need for smaller time step
- Future: Upgrade for 3-DOF configuration

Patrick Covi – Hybrid fire testing of virtual steel frame

Fire Hybrid testing

- Nonlinear finite element/analysis – structural behaviour is strongly nonlinear (material/geometry)
- Integrated with Newmark (gamma = ½ and beta = 0) (which is equivalent to the Central Difference (CD) method)
- Dynamic relaxation algorithm – with fictitious mass and stiffness
- Nonlinear thermo-mechanical beam finite element
- Virtual hybrid test (case study) in MATLAB framework

SERA

- European Project SERA EQUFIRE – sequential seismic + fire by geographically distributed testing
- EQUFIRE: a case study of a CBF
- 2D frame in OpenSEES and SAFIR as reference solutions
- Geographic distribution – one column test in a furnace at BAM, ground floor in JRC, and rest numerically (UNITN/ETH); loads then applied to the column; the column is subjected to fire hybrid simulation
- Some delays due to internet
- 5 proposed tests:
    - Frame without fire protection
    - Several tests with different fire protection
    - Structure with fire wall (seismic only)

Summary:

The concept of a Hybrid Test is very simple, in fact, we can physically build only the part that we want to study or some element that it's difficult to simulate its behaviour and all the other part is simulated in a computer.

For example, if we want to study only a column of this building under fire load, we built physically only this column and we put it inside a furnace with some actuators at the end of the column to reproduce boundary conditions. The rest of the building will be simulated with HFS inside a computer.

During the column test in the furnace, the simulation software continually increases or decreases the column load based on the variation of the column deflections. The variation in the column deflections is continually used by the software to simulate the effect on the rest of the structure.

For study structures on fires, a nonlinear finite element and in general a nonlinear analysis is needed because the behaviour of structures and elements subjected to fire loads are strongly non-linear.

There are two types of nonlinearities: geometrical and mechanical.

ETHZ/UNITN developed a MATLAB framework for finite element analysis with domain decomposition coded in house. A nonlinear thermo-mechanical beam element is included in the framework to be used for the simulation of the thermomechanical behaviour of steel elements.

This framework is based on Finite Element Tearing and Interconnecting (FETI) algorithm. In particular, it relies on the Gravouil and Combescure (GC) algorithm and the Localized Lagrange Multipliers (LLM) method to couple multiple PS and NS. A Dynamic relaxation (DR) algorithm is adopted to build an equivalent dynamic system that mimics the static response of substructures. In order to maximize the convergence rate of DR, Component-mode synthesis (CMS) is used to derive reduced-order matrices for both PS and NS.

For the geometrical nonlinearity, the corotational formulation is used, in order to consider second-order deformations on members induced by large displacements.

For the mechanical nonlinearity, the Stress-strain relationship for carbon steel at elevated temperatures is used and also the degradation of mechanical properties at elevated temperatures is considered, according to the Eurocode 3 part 2.

Then, the effectiveness of the proposed method is demonstrated on a virtual experimental campaign. A three-storey three-bay moment-resisting frame was selected as a case study for the virtual HFS campaign. It is designed according to the Eurocode 3 considering an S235 steel grade. All beams and columns are characterized by standard commercial metric cross-section without any fire protection. Only ground floor columns and first-storey beams are subjected to fire loading whilst the upper part of the frame remains at ambient temperature.

This frame was partitioned into two substructures, where both NS and PS were simulated numerically into the MATLAB™ framework and validated against reference FE solutions (SAFIR™). Each element of the NS is subdivided into six linear Bernoulli elements and each element of the PS is subdivided into six nonlinear thermo-mechanical beam elements. Only the translational DOFs at the boundary conditions between the two subdomains are taken into account, according to the most typical setup in a laboratory.

Since the HFT campaign is virtual, a nonlinear FE model was used to obtain the response of the hot PS.

The time-history response of the frame obtained via real-time simulations showed good agreement between the monolithic and the partitioned solutions. The validation carried out in a fully numerical framework shows promising outcomes for future experimental implementations and it will be soon applied on a real experiment planned within the Transnational Access EQUFIRE within the European Unions Horizon 2020 SERA Project.

SERA is a Horizon 2020-supported programme involves 31 partners and 8 linked third parties in Europe. It started in May 2017 and will last for three years.

The objective of EQUIFIRE is the multi-hazard performance assessment of structural and non-structural components subjected to seismic and fire following earthquake by means of geographically distributed testing. Access to the ELSA Laboratory at the Joint Research Centre (Ispra, Italy)

Fires following earthquake have produced historically large post-earthquake damage and losses, in terms of life, buildings and economic costs.

As far as thermomechanical coupled analysis for hybrid dynamic simulations (HDS) is concerned, fires following earthquake can be ignited due to, for instance, failure of gas lines and of power lines. They can be a serious problem, especially if the water lines that feed the fire hydrants are broken too and the infrastructural network has undergone significant disruptions.

The prototype structure will be a four-storey steel concentrically braced frame. For the braces, IPE sections will be used.

The 2D frame was modelled in OpenSees and SAFIR™ to obtain the reference solutions.

Some geographically distributed FFE hybrid tests will be carried out. The ground floor of the concentrically braced frame will be substructured at the ELSA Laboratory at the Joint Research Centre (JRC, Ispra, Italy) and at the BAM (Bundesanstalt für Materialforschung und –prüfung, Berlin, Germany) facilities (one column inside the furnace of BAM and all the other elements of the ground floor will be at JRC). The remainder of the structure will be simulated numerically according to the finite element method inside a pc at UNITN (University of Trento, Trento, Italy) and/or ETH Zurich (Swiss Federal Institute of Technology, Zurich, Swiss). This NS will be kept at ambient temperature through the test. In particular, at the JRC the designated element will be tested against lateral cyclic loading at ambient temperature, whilst it will be subjected to the fire at BAM, simulating the fire after earthquake loading. One test will be without any fire protection on elements and in other tests, there will be different type of fire protection on the elements. The last test will be the structure with fire wall in two bays (seismic test only). The results will be also used to validate the MATLAB framework.

Silvio Renard – An adaptive controller for hybrid fire testing

- Goals: ensure compatibility / equilibrium at ends of component during furnace testing
- Common existing methodologies use the initial stiffness
- Adaptive sliding mode controller:
    - Drives the displacements towards the vicinity of error = 0 surface
    - Can overadapt; exhibits oscillations and slow reactivity
    - Modified with a "maximum reachable precision zone" to correct for over-adaptation
- Virtual hybrid fire test framework as a middleware using two SAFIR instances for non-linear substructures
- Case study comparing three controllers: proportional, proportional integral and adaptive controller
- Added imperfections to check algorithm robustness
- Future works: better differentiator for the error, use of the velocity output to drive the servo-valve directly, extensions to floating sub-domains, implementation for a multi-degree-if-freedom full scale fire test

Summary:

Exiting methodologies for hybrid fire testing (HFT) use precise estimation of the stiffness of the physical substructure (PS) in order to ensure the stability of the iterative procedure. Usually this estimation is made for the initial tangent stiffness. This tangent stiffness is subject to large changes during the fire test and it can lead to the loss of the stability and the accuracy of the HFT. On the other hand, a real time estimation of this tangent stiffness is a challenging task. The adaptive sliding mode controller is designed to be unconditionally stable without explicitly needing the knowledge of the PS stiffness. The presented methodology imposes the compatibility between the two substructures and measure the equilibrium error, then a controller changes the imposed displacements based on this error. The principle of this controller is to define a surface on which the equilibrium error exhibits an exponential decay. Then an adaptive controller forces the system to cross this surface at each iteration. This controller does not output the displacements directly but its acceleration. The displacement is hence calculated with a double time integration. The study developed a virtual HFT framework around a control program to communicate with two instances of the SAFIR finite element software, to simulate both the numerical substructure and the PS and to verify the performances of various control algorithms. A case study of a nonlinear structure is presented in order to compare the performance of the existing proportional and proportional integral controller with the presented adaptive controller. The command of the velocity of the actuators can be achieved without modification of this controller and could tackle the problem of the large forces spikes due to the thermal expansion of the specimen between two displacement actualizations. Some limitation of the presented controller are: the lack of precision at the beginning of the test in the presence of strong measurement errors and non-obvious extension to floating substructures.

Elke Mergny – PI-Control in Hybrid Fire Testing

- PI-control – stability not affected by delay; but delay is related to sampling time for accuracy
- Dynamics matrix does not depend on error of measurement (but is affected by accuracy)
- Dynamics matrix depends on stiffness of all substructures – physical sub-structure stiffness can only be estimated (PI controller sensitive to this)
- Initially assume design using initial stiffness is sufficient
- Focuses on sensitivity of controller to initial stiffness
- Virtual hybrid fire testing (all sub-structures modeled numerically)
- In case of under-estimation of stiffness – eigenvalues larger than 1 (instability); negative real part – sign of possible oscillations
- Not very sensitive to over-estimation of stiffness (and low under-estimation)
- PI controller is robust for large delays and overestimation of physical stiffness
- Sensitive to under-estimation of physical stiffness

Reto Grolimund – A coupled experimental and numerical framework for the analysis of steel structures subjected to fire

- Simplified numerical model representing sub-structure
- Does local member failure lead to global collapse?
- Multi-solver approach; axial load increases until buckling
- Up to buckling – static solver (nonlinear static)
- past buckling – nonlinear dynamic procedure
- Upon stability – nonlinear static procedure
- For the numerical-experimental assessment of the full global response to fire – need for dynamic solution procedure
- Thermo-mechanical structural response must be obtained in real-time1

Summary:

A four storey steel buildings with a fire at the ground floor compartment was selected as a case study. A simplified model was building. The Physical substructure (PS) is the column at ground floor and the numerical substructure is the first-storey beam and is basically a linear elastic spring. The upper part of the structure is represented with a vertical force and the mass of the upper storey is taken into account. 5% of damping is considered. The load protocol is divided into two stages, first just increase the load and in the second stage, it starts the fire scenario.

For practical use they used the control software of machine manufacturer to predict the displacement commands and this control software is very slow, so at the moment it is not possible to do a real-time hybrid test on this setup but they can employ static and implicit dynamic solution algorithm with the same framework and it can switch automatically.

First, it increases the load and due to the thermal expansion, the axial load on column increase until there is the buckling of the column. When it is not possible to find static equilibrium anymore, the algorithm automatically switches to a dynamic implicit procedure with different time scale because there is a delay (0.8 s) between the command of the finite element and the displacement in the actuator.

Giuseppe Abbiati – A real-time hybrid fire simulation algorithm based on dynamic relaxation

- Difference between seismic hybrid testing and fire hybrid testing
  - Axial force is variable during fire development.
- The frequency bandwidth must be compatible with the actuators.
- Dynamic relaxation - fictitious mass and damping matrix that are functions of the stiffness matrix
- Is actually the closest methodology that it will be used in the SERA EQUFIRE project.

Summary:

Fires are typically modelled time-temperature curves. The ground floors start expanding and this expansion is blocked by the upper part of the prototype structure, which is cold. So there is force distribution in the substructures in terms of moments and axial forces. Many of these tools for hybrid simulation are based on earthquake engineering and in the fire case there is exactly the complementary situation. The axial force is variable during the fire development due to the restrained thermal expansion and we have a statical response. The frequency bandwidth of the prototype structure is calculated considering the maximum eigenfrequency of the prototype of the structure divided by the testing time scale. We obtain the real frequency that we are excited in the laboratory, so this is the real frequency of the dynamic system. Something that is compliant with the frequency bandwidth of the actuator system. If we want to include axial distribution, it is necessary to add some other actuator in different positions and of course the frequency bandwidth of the prototype structure starting increasing because we are including higher modes of the systems which are characterized with a very high stiffness and a low mass.

The idea to solve this problem is with dynamic relaxation and in particular fictitious mass and damping matrix that are functions of stiffness matrix and force the frequency bandwidth of the system to stay in a frequency range that is compatible with the normal actuators. The basic idea is to solve an equivalent dynamic equation of motions where mass and damping are fictitious.

Is actually the closet methodology that it will be used in the SERA EQUFIRE project.