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HYBRID SIMULATION OF LARGE-SCALE STRUCTURES AT ETH ZÜRICH: THE NEW MULTI-AXIAL SUBASSEMBLAGE TESTING SETUP

G. Abbiati[(1)], C. A. Whyte [(2)], V. K. Dertimanis [(3)], B. Stojadinovic[(4)]

[(1)] *Postdoctoral Researcher, Department of Civil, Environmental and Geomatic Engineering (D-BAUG), IBK, ETH Zurich, Switzerland, abbiati@ibk.baug.ethz.ch*
[(2)] *Postdoctoral Researcher, Department of Civil, Environmental and Geomatic Engineering (D-BAUG), IBK, ETH Zurich, Switzerland, whyte@ibk.baug.ethz.ch*
[(3)] *Postdoctoral Researcher, Department of Civil, Environmental and Geomatic Engineering (D-BAUG), IBK, ETH Zurich, Switzerland, v.derti@ibk.baug.ethz.ch*
[(4)] *Professor, Department of Civil, Environmental and Geomatic Engineering (D-BAUG), IBK, ETH Zurich, Switzerland, stojadinovic@ibk.baug.ethz.ch*

Abstract
In the last two decades, hybrid simulation has received increasing attention from the earthquake engineering community as a tool for simulating the nonlinear dynamic response of large structural systems in facilities with limited capacities. The quality of the simulation strongly depends of the correct application of the interface boundary conditions between the numerical and the physical subdomains. Nevertheless, the need for reducing costs and efforts related the experimental setup usually forces the partial relaxation of coupling conditions e.g., discarding interface rotational degrees-of-freedom. In this scenario, re-usable multi-axis subassemblage testing loading systems represent a convenient trade-off between achievable coupling fidelity degree and experiment cost. Along this line, this paper revisits state-of-the-art setups and presents our recent developments on this direction at the Swiss Federal Institute of Technology (ETH) in Zurich.

Keywords: Hybrid Simulation, Kriging Metamodeling, Gaussian Process, Active Learning, Adaptive Experimental Design.

1 Introduction

In the last two decades, Hybrid Simulation (HS) has received increasing attention from the earthquake engineering community as a tool for simulating the nonlinear dynamic response of large structural systems in facilities with limited capacities [1,2,3,4,5]. In particular, only critical components of the assembly, which lack reliable numerical models, are substructured in the laboratory where a loading system imposes the correct boundary conditions, and the remainder is simulated using Finite Element (FE) analysis software [6,7]. The quality of the simulation strongly depends of the correct application of the interface boundary conditions between the Numerical and the Physical Subdomains (NS and PS) of the hybrid model. In principle, compatibility of displacements and rotations and balance of forces and moments must be satisfied. Nevertheless, HS was conceived for reducing costs and efforts normally encountered in large-scale structural testing. Such principle comes with a burden to design often non-reusable and always complex loading systems, which guarantee a full coupling between NS and PS, but need a lot of engineering to be implemented and testing skill when used. As a consequence, full NS-PS coupling conditions are very often relaxed, at least in part, e.g. by discarding rotational DOF coupling at the NS-PS interface. In this scenario, re-usable devices represent a convenient trade-off between achievable degree of coupling fidelity and the HS costs. The class of loading systems to which we are referring to is gaining more and more popularity under the name of Multi-Axis Substructure Testing (MAST) systems. A MAST system combines actuators, frames and platforms into an optimized device that can handle a full node-wise coupling, i.e. 3 translations and 3 rotations, between the NS and the PS. Such devices can be installed on reaction walls, strong floors or combined with additional frames as a versatile functional block of the test setup. Also important, MAST devices can easily be used to perform conventional static and quasi-static cyclic tests on structural components.

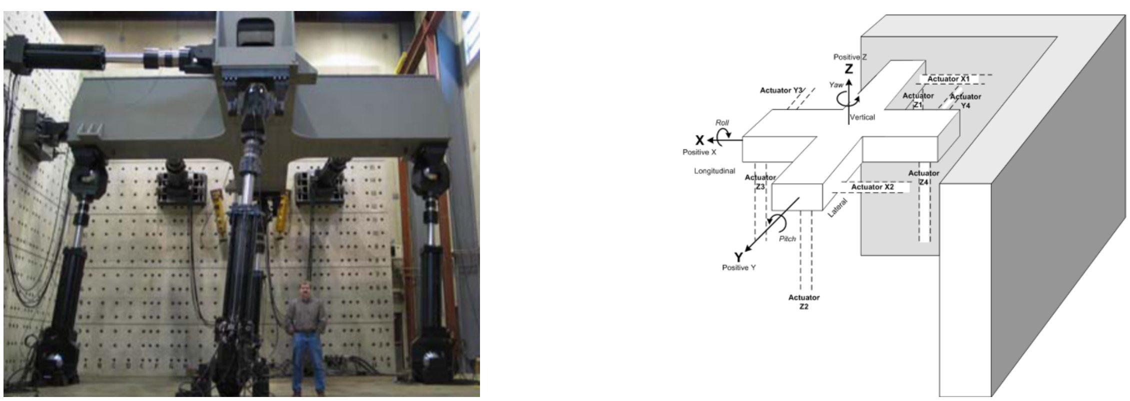
In order to emphasize major challenges of MAST loading system development, it must be stressed that displacement-control actuation is impracticable when stiff DOFs, i.e. ones activating axial member deformations, are involved. In this case, small perturbations of the displacement field, even of the order of the magnitude of setpoint tracking accuracy, generate large force oscillations, which hinder the dynamic stability of HS. Multiple coupled DOFs further amplify such effect triggering unstable actuator interactions. For this reason, gravity loads are usually applied with force-control actuators. On the other hand, displacement-control actuators work in the horizontal direction activating mainly softer flexural and shear element deformation. Nevertheless, control partitioning in a MAST loading systems is not straightforward anymore: here the same set of vertical actuators simulates gravity load and imposes roll and pitch rotations at the same time. In this case, each actuator participates to both displacement/rotation and force/moment tracking and therefore, a multiple-input-multiple-output (MIMO) multi-objective (MO) control strategy represents a mandatory choice. In addition, if the number of displacement-control actuators entail redundancy of constraints, a force balance compensator must redistribute the workload among jacks. Arguably, more than ammechanical linkage, designing an effective controller is indeed the main challenge encountered in the development of MAST loading systems.

Given this premise, this paper revisits a number of existing state-of-the-art MAST systems and presents our recent developments in this direction. In detail, an 8-actuator 6-DOF MAST setup based on a 15.12 m x 11.52 m steel crosshead is designed to support large-scale HS at the Swiss Federal Institute of Technology (ETH) Zürich. Both ongoing developments and remaining challenges are discussed.

2 Review of existing multi-axial subassemblage testing setups

2.1 MAST setup at the Minnesota University

The MAST setup at the Minnesota University [8], Minnesota MAST hereinafter, is part of the US funded George E. Brown Jr. Network for Earthquake Engineering Simulation project [9]. It enables multi-axial quasi-static cyclic tests of large structural subassemblages including portions of beam-column frame systems, walls and bridge piers. One of the key features of the system is the employment of a 6-DOF controller that allows for mixed mode control. Figure 1 provides an overview on the Minnesota MAST loading system.

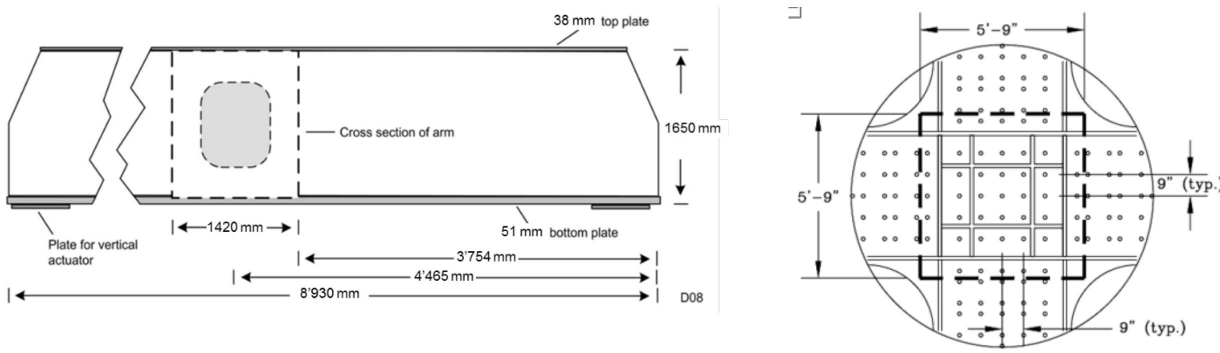


(a) (b)

Fig. 1 - Minnesota MAST loading system: (a) picture of the test setup; (b) schematic of the loading frame with coordinate system highlighted.

As can be appreciated from Figure 1, 4 vertical actuators carry the steel crosshead and are fixed to the strong floor. Analogously, 4 horizontal actuators, which are secured to the L-shaped strong wall, impose lateral displacements. Hydrostatic bearings are used in conjunction with vertical actuators to reduce friction loads and vertical spacers can be mounted between bearings and vertical actuators for height clearance adjustment. The strong floor measures 10.7 x 10.7 m in plan and provides an array of 140 mm thick threaded steel plates post-tensioned to a 2.1 m thick concrete slab. 76 mm diameter threaded holes in the slab provide a rectangular anchor pattern with center-to-center spacing of 460 mm, with a service load capacity of each hole of 560 kN in both vertical (axial) and horizontal (shear) directions. Each inside leg of the L-shaped 10.7 m tall reaction wall provides the same regular anchor pattern of 460 mm spacing. Moreover, walls are post-tensioned to the foundation so as to increase stiffness. The Minnesota MAST can accommodate specimen of approximately 6.1 x 6.1 m base area and 8.6 m height.
The steel crosshead is characterized by a 1.42 x 1.65 m box section. In detail, a continuous 50 mm thick bottom plate is welded to 38 mm thick webs, which are connected to the 38 mm thick top flange. The whole crosshead

weights 42.6 ton. An additional bottom plate and a set of vertical ribs strength the crosshead core, where the specimen is connected. The four arms are equal and measure 4.46 m from core-center to tip. Figure 2 reports a schematic view of the steel crosshead.



(a) (b)

Fig. 2 - Schematic of the steel crosshead of the Minnesota MAST loading system: (a) arm with main dimensions; (b) detail of core ribs.

Table 1 summarizes the loading capacity of the Minnesota MAST while Table 2 reports actuator characteristics.

Table 1 - Minnesota MAST loading capacity.

DOF	Load	Deformation
X	± 3920 kN	± 400 mm
Y	± 3920 kN	± 400 mm
Z	± 5880 kN	± 500 mm
Rx (roll)	± 13671 kNm	± 7 degrees
Ry (pitch)	± 13671 kNm	± 7 degrees
Rz (yaw)	± 36456 kNm	± 10 degrees

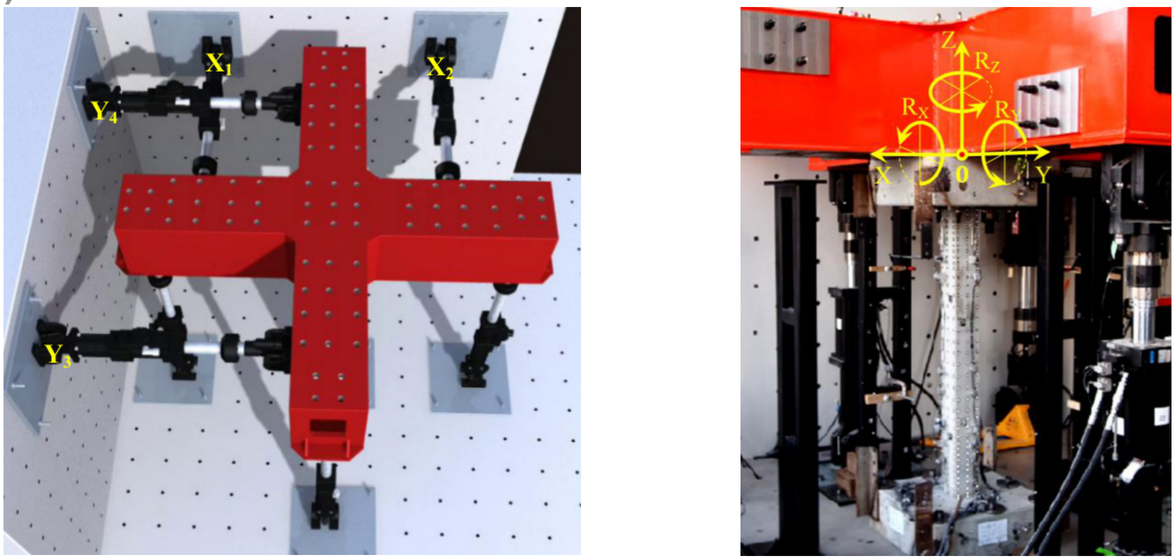
Table 2 - Minnesota MAST actuator capacity.

Direction	Vertical	Horizontal
Force capacity	1470 kN	1960 kN
Stroke	± 510 mm	± 400 mm

The Minnesota MAST facility provides extensive telepresence capabilities to support both documentation of experiments and remote collaboration. On-site and remote collaborators can participate in experiments through control of camera devices and information flow. Real-time data streaming is available anywhere via high-speed internet connection.

2.2 MAST setup at the Swinburne University of Technology

The MAST setup at Swinburne University of Technology [10], Swinburne MAST setup hereinafter, provides a state-of-the-art facility for mixed-mode large-scale quasi-static cyclic testing and local/geographically-distributed HS. Figure 3 depicts the Swinburne MAST and the specimen accommodation with local coordinate system highlighted.



(a) (b)

Fig. 3 - Swinburne MAST: (a) overview of the testing setup; (b) specimen accommodation with coordinate system highlighted.

As can be appreciated from Figure 3, 4 vertical hydraulic actuators combined with 4 horizontal hydraulic actuators in orthogonal directions handle a 9.5 ton steel crosshead, which transfers loads/displacements to the specimen. In detail, actuators are secured to a reaction system based on an 8 x 8 m wide 5 m tall 1 m thick concrete wall and strong floor, which is 1 m thick. The maximum specimen size allowed is 3 x 3 m wide by 3.25 m tall. A 3-loop hybrid simulation framework based on SCRAMNET-OpenFresco-OpenSees architecture [11,12] handles the servo-hydraulic control loop, which imposes 6-DOF boundary conditions in switched and mixed mode control. High-precision draw-wire displacement encoders with a resolution of 25 mu can provide additional external feedback measures. Force balance control is used to manage constraint redundancy in the actuation system: since 8 actuators handle 6-DOF, the Swinburne MAST is an over-constrained system. As such, infinite actuator forces can still satisfy a given displacement profile. Force balance compensation redistribute forces among all actuators so as to uniform the workload. Table 3 summarizes the loading specifications of the Swinburne MAST while Table 4 reports actuator capacities.

Table 3 - Swinburne MAST loading capacity.

DOF	Load	Deformation
X	1000 kN	± 250 mm
Y	1000 kN	± 250 mm
Z	4000 kN	± 250 mm
Rx (roll)	4500 kNm	± 7 degrees
Ry (pitch)	4500 kNm	± 7 degrees
Rz (yaw)	3500 kNm	± 7 degrees

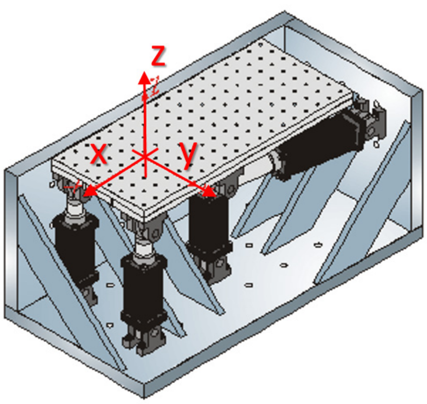
Table 4 - Swinburne MAST actuator capacity.

Direction	Vertical	Horizontal
Model	MTS 244.51	MTS 244.41
Force Capacity	± 1,000 kN	± 500 kN
Stroke (static)	± 250 mm	± 250 mm
Stroke (dynamic)	± 150 mm	± 150 mm

As anticipated a three-loop architecture characterize the HS environment. The MTS FlexTest 100 Servo-Controller represents the innermost loop, which sends force/displacement commands to the MAST and reads measured feedbacks. An xPC-Target real-time computer hosts the middle loop where a predictor-corrector algorithm interpolates/extrapolates actuator commands, which are sent to the MTS FlexTest 100 through the SCRAMNET shared memory. The xPC-Host, which includes OpenSees, Matlab and OpenFresco, runs the outer time integration loop and communicate with xPC-Target via TCP/IP. OpenSees, which is deeply integrated with OpenFresco simulates the NS response.

2.3 MAST setup at the Illinois University

The Illinois MAST setup [13] is one of the equipment sites form the George E. Brown Jr. Network for Earthquake Engineering Simulation [9]. This facility enables testing of full-scale subassemblies under complex loading and boundary conditions. In detail, up to three Loading Boundary Condition Boxes (LBCBs) can be used to compose the MAST loading system. The LBCB platform is a loading and boundary conditions point where any combination of three forces and three moments (three rotations and three translations) can be easily controlled. The LBCBs provides 6-DOF control and consists of a reaction box equipped with six actuators of 1001/1383 kN tension/compression capacity and a loading platform. LBCBs can be fixed to the strong floor, to the reaction wall and to an additional steel reaction frame, which allows for applying loads to specimen from top. The overall dimensions of the reaction box are approximately 3.6 m long, 1.8 m wide and 1.8 m high. The loading platform is approximately 2.2 m long and 1.9 m wide. Three vertical actuators are used to control z displacement, theta-x (roll) and theta-y (pitch) rotation of the loading platform. Two horizontal actuators control x displacement and theta-z (yaw) rotation. One additional horizontal actuator controls the y translation of the loading platform. Pillow block spherical hinges connect the actuators to the loading platform and to the box. Figure 4 offers a schematic view of the LBCB and its application for concrete column testing.



(a)

(b)

Fig. 4 - LBCB: (a) schematic of the loading platform; (b) testing of a column specimen.

Table 5 summarizes the loading capacity of the Minnesota LBCB element.

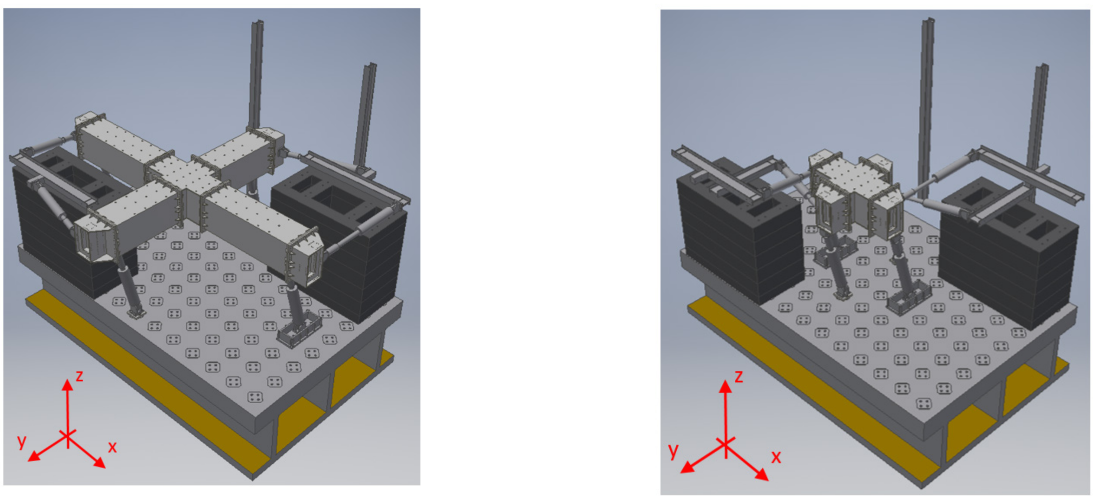
Table 5 - Minnesota LBCB loading capacity.

DOF	Load	Deformation
X	1921/2918 kN Tension/Compression	± 250 mm
Y	960/1459 kN Tension/Compression	± 250 mm
Z	2882/4377 kN Tension/Compression	± 125 mm
Rx (roll)	± 862 kNm	± 16 degrees
Ry (pitch)	± 1152 kNm	± 11.8 degrees
Rz (yaw)	± 862 kNm	± 16 degrees

The Illinois MAST facility is equipped with an L-shaped post-tensioned concrete strong wall of 15.2 x 9.1 x 8.5 x 1.5 m (length x width x height x thickness), which enables testing of full-scale substructures. The wall is post-tensioned to a 5.2 m thick box-girder. The LBCBs are portable so that they can be anchored on any reaction structure that has a compatible pattern of anchorage holes.

3 Description of the MAST setup at the ETH Zürich

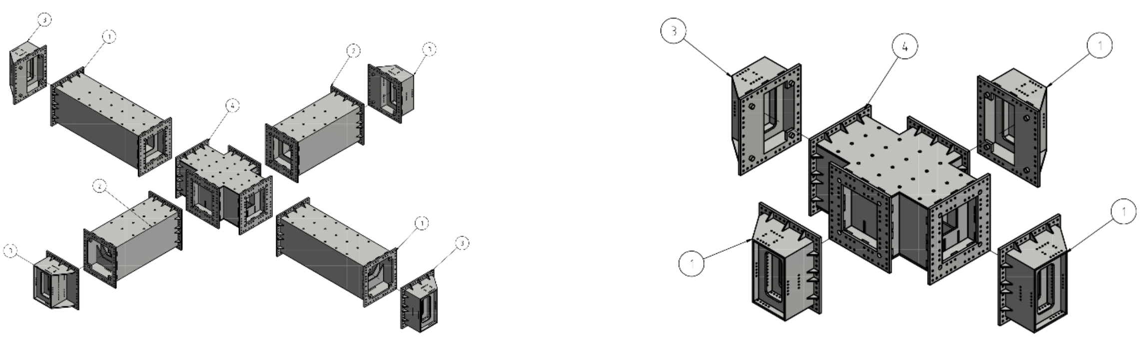
The MAST setup of ETH Zürich, ETH Mast hereinafter, relies on a modular steel crosshead for loading the specimen. As we write, the design phase is just concluded and the beginning of the construction of the MAST loading system is forthcoming. Two testing configurations of the crosshead are allowed: i) one based on long arms with overall dimensions of 15.12 m x 11.52 m, which incorporates large specimens e.g., small buildings or long reinforced concrete walls; ii) one based on short arms with overall dimensions of 5.36 m x 4.16 m, which incorporates specimens with narrow profiles e.g., columns or a bearings. The vertical clearance under the crosshead is 4.39 m for both the two configurations. Figure 5 gathers the 3d rendering of the ETH MAST setup in the long- and the short-arm configurations.



(a) (b)

Fig. 5 - 3D views of the MAST setup: (a) long-arm and (b) short-arm configurations.

As can be seen in Figure 5, 4 horizontal and 4 vertical actuators handle the MAST crosshead and the reader must be aware that steel boxes connecting actuators to concrete towers are not reported in this sketches. In the long-arm configuration, the ETH MAST can apply the largest moments to the specimen. In the short-arm configuration, the ETH MAST can apply larger rotations but smaller moments. The maximum lifting capacity of the facility is 20,000 kg. As a result, the 72.5 ton ETH MAST crosshead is partitioned in multiple elements as shown in the exploded views of Figure 6.



(a) (b)

Fig. 6 - Exploded view of the MAST crosshead: (a) long-arm configuration; (b) short-arm configuration.

Crosshead arms are characterized by 1450 x 1600 mm box cross-sections made out of plate of 40 mm thickness. Here, the axes of the horizontal actuators are 800 mm apart (in the vertical z direction) to avoid crossing paths. This introduces a vertical eccentricity of 400 mm for each actuator. Table 6 and 7 reports element and assembly masses for both long- and short-arm configurations.

Table 6 - Elements of the MAST crosshead in the long-arm configuration.

Element	Description	Quantity	Mass [kg]	Total mass [kg]
1	Long-arm	2	12450	24900
2	Short-arm	2	9751	19502
3	Actuator connector	4	2956	11824
4	Core	1	16274	16274
			TOTAL	**72500**

Table 7 - Elements of the MAST crosshead in the short-arm configuration.

Element	Description	Quantity	Mass [kg]	Total mass [kg]
3	Actuator connector	4	2956	11824
4	Core	1	16274	16274
			TOTAL	**28098**

Force transmission from steel crosshead to specimen is critical. As a result, the core element is heavily reinforced with ribs. Figure 7 shows an exploded view of the crosshead core.

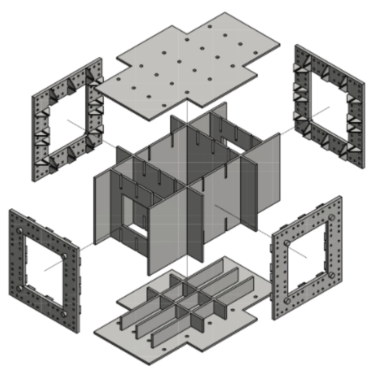


Fig. 7 - Exploded view of the crosshead core.

Figures 8 and 9 depict the schematics of the steel crosshead for both short- and long-arm configurations, including the locations of horizontal and vertical actuator attachment points.

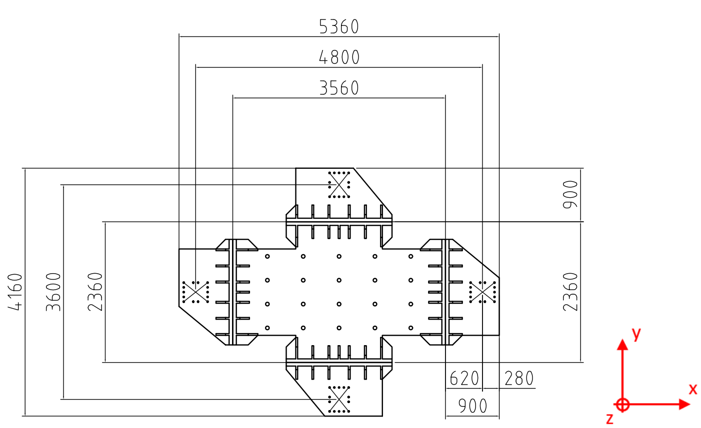


Fig. 8 – Schematic of the crosshead short-arm configuration with main dimensions in mm.

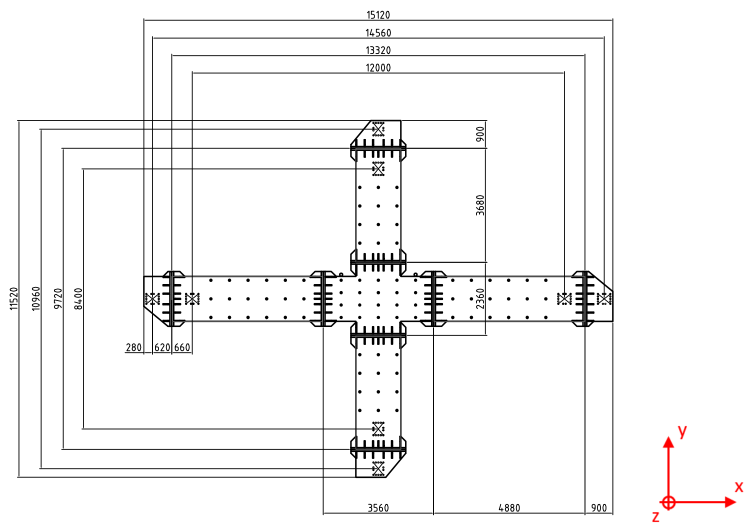


Fig. 9 – Schematic of the crosshead long-arm configuration with main dimensions in mm.

Table 8 and 9 summarize the loading performance of the ETH MAST setup while Table 10 reports actuator capacities.

Table 8 - ETH MAST loading capacity for the long arm configuration.

DOF	Load	Deformation
X	± 2000 kN	± 600 mm
Y	± 2000 kN	± 600 mm
Z	± 10000 kN	± 600 mm
Rx (roll)	± 21000 kNm	± 8.13 degrees
Ry (pitch)	± 30000 kNm	± 5.71 degrees
Rz (yaw)	± 25520 kNm	± 4.71 degrees

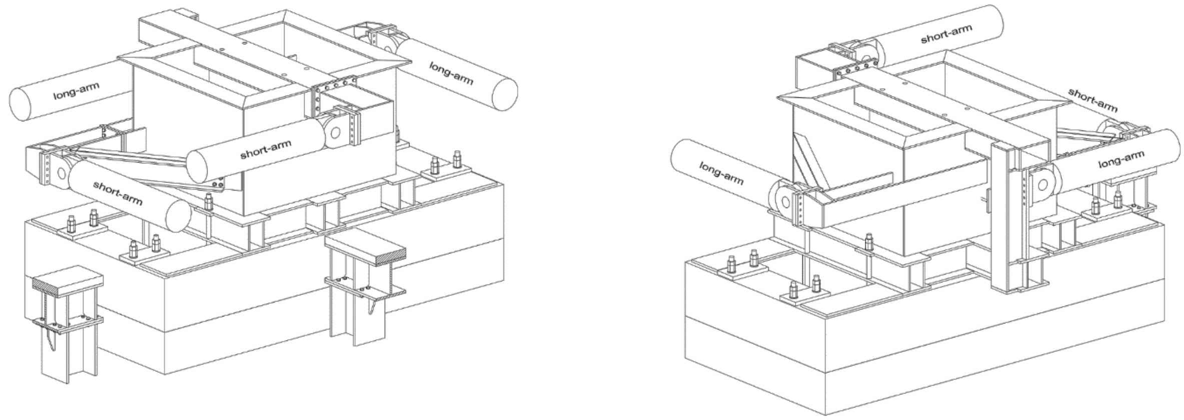
Table 9 - ETH MAST loading capacity for the short arm configuration.

DOF	Load	Deformation
X	± 2000 kN	± 600 mm
Y	± 2000 kN	± 600 mm
Z	± 10000 kN	± 600 mm
Rx (roll)	± 9000 kNm	± 18.43 degrees
Ry (pitch)	± 12000 kNm	± 14.03 degrees
Rz (yaw)	± 8400 kNm	± 14.03 degrees

Table 10 - ETH MAST actuator capacity.

Direction	Vertical	Horizontal
Force capacity	2500 kN	1000 kN
Stroke	± 600 mm	± 600 mm

Two post-tensioned concrete tower will secure horizontal actuators while vertical ones will be fixed to the strong floor, which is 1 m thick. Each tower is conceived as a stack of 6 concrete blocks supporting a steel box where actuators are connected and it is designed to carry bending moments up to 5680 kNm and 5280 kNm along x and y directions, respectively. A total of 20 post-tensioning bars will provide an overall vertical compression preload of 20 MN, which will prevent from tensile stresses within horizontal concrete cross-sections. Figure 10 gathers two close up views of the steel-box structure that connects actuators to the concrete tower.



(a) (b)

Fig. 10 - Actuator-to-tower steel connection box: (a) inner side; (b) outer side (with respect to the crosshead).

In view of performing testing campaigns based on HS, specific classes will be implemented in the OpenFresco [11] middleware to handle the ETH MAST control system. OpenFresco is deeply integrated within the OpenSees [12] structural FE framework, which is therefore selected to simulate the NS. Figure 11 depicts the class architecture of OpenFresco.

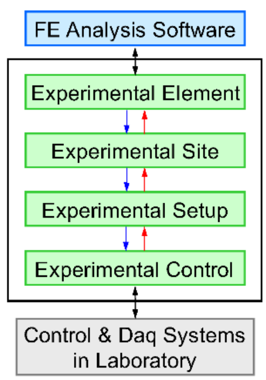


Fig. 11 - OpenFresco class diagram.

As depicted in Figure 11, the FE software sends displacement commands (blue arrows) to OpenFresco classes (green boxes) and receives restoring forces (red arrows). In detail:

- The *ExperimentalElement* class represents the PS in the FE software.
- The *ExperimentalSite* class represents the testing facility.
- The *ExperimentalSetup* class handles the coordinate transformation between prototype model and actuator coordinate systems.
- The *ExperimentalControl* class interfaces OpenFresco to the control system in the laboratory.

In this respect, Kim [14] developed new *ExperimentalControl* classes for force- (*ECForce*), mixed- (*ECMixed*), and switch-control (*ECSwitch*), which convert displacement-based commands from the FE software to force-based commands. The existing mixed-mode control library will be extended to handle the 6-DOF crosshead loading system to handle the PS. Mixed-control allows for combining force and displacement controllers within the same setup when stiff DOF are involved. Moreover, force compensation will be included to distribute the workload among jacks.

The mechanical hybrid simulation capability of the ETH MAST facility can be combined with the existing modular electric furnace to enable thermomechanical hybrid simulation (TMHS). The furnace modules can be combined to enclose a variety of column and joint specimen configurations and are capable of delivering the heat required to simulate and ISO 834 temperature-time fire curve and reach temperatures of up to 1000^{o}C. Extensions of the OpenSees and OpenFresco to implement TMHS have already been made [15].

4 Conclusions

Degree of fidelity of HS in replicating prototype system response strongly relies on the capacity of the experimental setup to reproduce interface boundary conditions between NS and PS. The re-usable and re-configurable MAST loading systems represent a convenient trade-off between versatility of allowable coupling configurations and experiment cost. This paper revisited a number of existing MAST setups and presented our recent developments at ETH Zürich in this direction. As we are writing, the design phase of the ETH MAST is concluding and the construction phase is forthcoming. Among all, in our opinion, designing an effective control strategy, which enables mixed-mode control and workload self-balance, is the most stimulating challenge still to be tackled.

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