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Design, Construction and Capabilities of the Large Universal Shell Element Tester

Diseño, construcción y capacidades del Large Universal Shell Element Tester

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ABSTRACT

The *Large Universal Shell Element Tester* (LUSET) is a new testing facility that has been developed at ETH Zurich. It enables the investigation of the load-deformation behaviour of full-scale reinforced concrete shell elements under arbitrary loading conditions. The motivation for the development of the LUSET is outlined followed by a description of the hardware and software components of the setup and the measurement systems used. Finally, the test series for validating the functionality of the LUSET is discussed and a general overview of the facility's overall testing capabilities is given.

KEYWORDS: Structural concrete, shell elements, combined loading, large-scale experiments.

RESUMEN

El *Large Universal Shell Element Tester* (LUSET) es un nuevo dispositivo de ensayos, desarrollado en la ETH Zúrich, el cual facilita el estudio del comportamiento mecánico, a escala real, de elementos lámina de hormigón armado sujetos a solicitaciones en sus tres dimensiones (esfuerzos combinados de elementos tipo losa y membrana). En este artículo se presentan los motivos que condujeron al desarrollo del LUSET y, adicionalmente, se describen sus componentes, el software de control y los sistemas de medición. Finalmente, se presenta una breve descripción de la serie de ensayos usada para validar la funcionalidad del LUSET, así como, un resumen de sus posibilidades.

PALABRAS CLAVE: Hormigón estructural, elementos lámina, solicitaciones combinadas, ensayos a gran escala.

1. INTRODUCTION

For the safe design of new concrete structures, models based on the lower bound theorem of plasticity theory are perfectly suitable. Hence, these models have been adopted by many design codes worldwide in the last decades. However, despite the suitability of limit analysis for the design of new structures, the method is often not applicable for structures built following older design codes and/or structures employing non-conventional reinforcements such as fibre and textile reinforced concrete. Therefore, more knowledge needs to be experimentally acquired regarding the load deformation behaviour of plate and shell structures not complying with the prerequisites of limit analysis methods. Furthermore, knowledge of the

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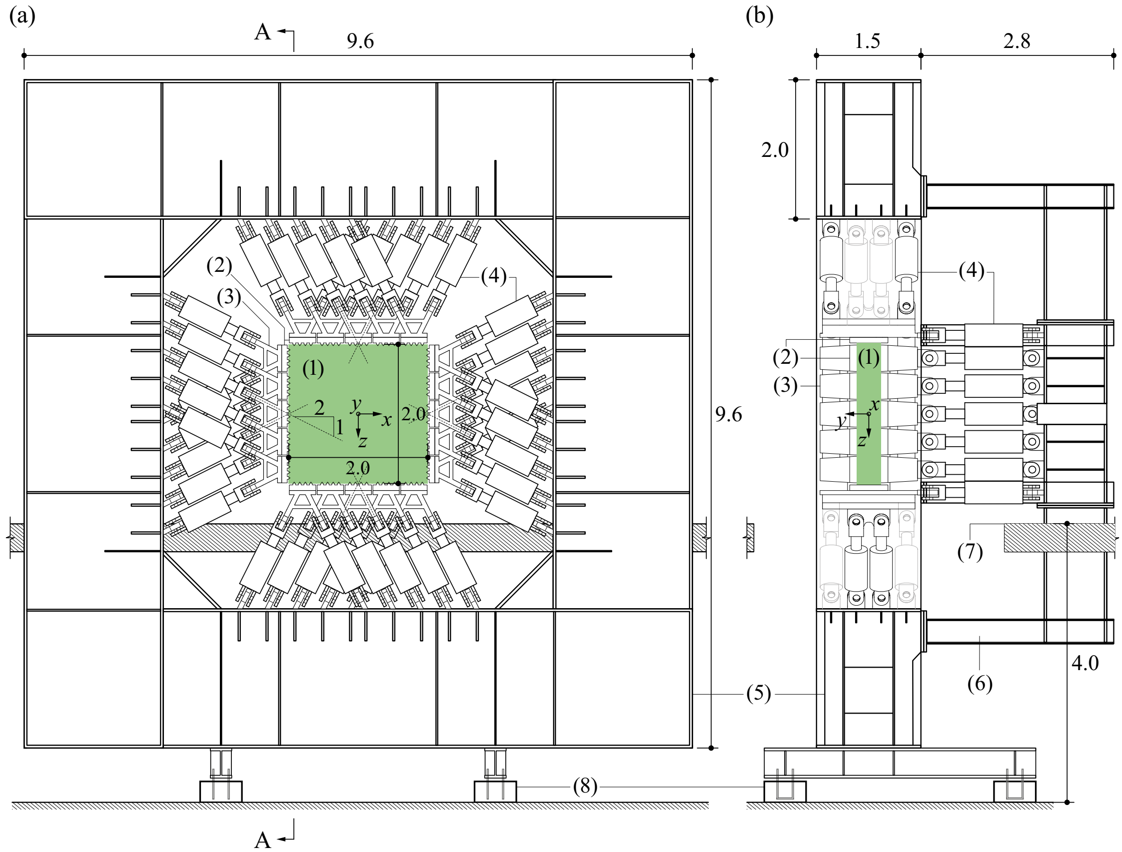

Figure 1. Overview of the LUSET: (a) elevation; (b) section A-A (dimensions in m); adopted from [1].

load-deformation behaviour is also important when checking serviceability criteria such as crack widths and deflections.

The LUSET enables the investigation of the load-deformation behaviour of large reinforced concrete shell elements under arbitrary loading conditions. This means, that the LUSET allows applying all eight independent stress resultants acting on generally loaded shell elements in any combination and arbitrary loading paths. Therefore, the conducted experiments on shell elements allow for (i) the investigation of the deformation capacity of structural concrete subjected to arbitrary load combinations; (ii) the exploration of the limits of applicability of the theory of plasticity to structural concrete with low amounts of reinforcement; and (iii) the critical review of current design provisions and available models. Hence, research carried out using this facility will hopefully contribute to avoid unnecessary strengthening of existing structures, and to design more efficient new structures.

This paper presents the design and construction of the LUSET and describes its testing capabilities and capacities.

2. FUNDAMENTALS

2.1 Basic Concept

The LUSET enables large-scale testing of reinforced concrete elements with in-plane dimensions of 2.0 x 2.0 m and a variable thickness of up to 0.38 m subjected to well controlled, arbitrary load combinations. Figure 1 shows an overview of the LUSET (elevation and section) with the main components and an installed specimen.

Along the edges of the specimen (figure 1, number (1)), the loads are introduced by means of 100 hydraulic actuators (4) acting on twenty independent loading yokes (3). In the reference position, the actuators are inclined at a ratio of 1:2, which corresponds to an angle of approximately 26.6° with respect to the outer normal of the specimen edge. The yokes are applying the loads to the blocks (2) which in turn transfer them to the specimen. The reaction forces of the actuators are equilibrated by a stiff in-plane reaction frame (5) and an out-of-plane frame (6). Due to the limited height of the structural laboratory, the supports of the reaction frame had to be placed in the basement of the building. Consequently, the installed specimens are located only slightly above the floor level of the laboratory (7), which facilitates the access during the experiments. In the basement, the LUSET is sitting on four concrete blocks (8), which carry the self-weight of the facility.

The control system is based on 20 servo-hydraulic valves such that in the standard configuration, 20 groups of five actuators can be controlled independently. The front and rear actuator chambers of each group of actuators controlled by one valve are hydraulically connected, such that the corresponding oil pressures are equal and thus, except for different frictional forces, they apply the same load. Four layers of five actuators are arranged in-plane and one group out-of-plane per specimen side.

100 displacement and 100 force sensors (one each per actuator) measure the strokes and forces of the actuators during the tests. Additionally, 20 tilt sensors monitor the yoke inclinations. The pressures in the two chambers of each valve are measured by pressure sensors (40 in total), which can also be used to determine the forces in the actuators.

The LUSET is built with a modular concept. This means that beside the standard machine configuration outlined above, there are possibilities to change the standard tests making use of the modular setup of the load introduction elements and the hydraulic components, as well as the control software. In particular, it is possible (i) to use different load introduction elements connecting to the yokes; (ii) to rearrange and reconnect the actuators with fast hydraulic connectors to arbitrary valves over a tube system; and (iii) to define arbitrary loading protocols with a Matlab interface for the control software. Hence, for tests diverging from the standard shell element tests with homogeneous loading conditions, it is also possible to introduce non-homogeneous loads such as shear and longitudinal strain with a gradient or even using only a part of the loading yokes. The modular setup will be outlined in more detail in section 5.

2.2 Capacities

Each of the five yokes per specimen edge is loaded by one out-of-plane actuator perpendicular to the middle plane of the specimen, with a specified capacity of +/-0.70 MN, and four in-plane actuators parallel to the middle plane of the specimen, with a specified capacity of +0.95/-1.35 MN. The horizontal spacing between the in-plane actuator axes is given as e = 0.36 m (see figure 2).

Figure 2 shows the forces introduced by the actuators into the yokes in red (P_{of}, P_{or}, P_{if}, P_{ir}, P_y) and the resulting loads introduced by the yokes to the specimen edge in green (n_x, n_{xz}, m_x, m_{xz}, v_x). For simplification, the blocks are not shown in this figure. The resulting loads can be expressed as functions of the actuator forces in the non-deformed state of the yoke and the specimen using the following equations.

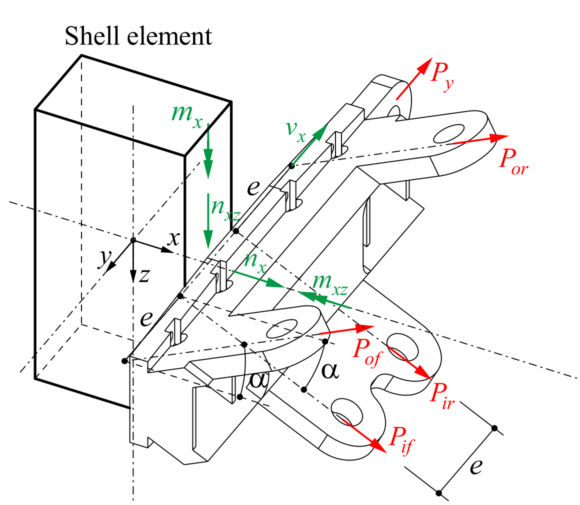

Figure 2. Notation of resulting loads introduced from the yoke into the specimen (green) and actuator forces acting on the yoke (red); adopted from [1].

$$n_x = \frac{P_e + P_{if} + P_{or} + P_{ir}}{0.40\ \text{m}} \cos\alpha$$

$$n_{xz} = \frac{-P_{of} + P_{if} - P_{or} + P_{ir}}{0.40\ \text{m}} \sin\alpha$$

$$m_x = \frac{(P_{or} - P_{of})1.5e + (P_{ir} - P_{if})0.5e}{0.40\ \text{m}} \cos\alpha + \frac{P_y\ 0.13\ \text{m}}{0.40\ \text{m}}$$

$$m_{xz} = \frac{(-P_{or} + P_{of})1.5e + (P_{ir} - P_{if})0.5e}{0.40\ \text{m}} \sin\alpha$$

$$V_x = \frac{P_y\ 0.13\ \text{m}}{0.40\ \text{m}}$$

From these relationships and the specified capacities of the in-plane and out-of-plane actuators, the loading capacities of the LUSET can be determined, see table 1. Note that these capacities are valid for each stress resultant individually, i.e., if the other stress resultants are zero. For example, in the case of the in-plane shear force nxz, this means that the maximum capacity is calculated with the tension capacity of all the actuators, such that a pure shear force is applied. The remaining stress resultants are obtained accordingly.

TABLE 1.
LUSET loading capacities.

Loading type		Capacity
Compression	n_x^c	12.07 MN/m
Tension	n_x^t	8.50 MN/m
Shear	n_{xz}	4.25 MN/m
Flexural moment	m_x / m_z	1.53 MNm/m
Torsional moment	m_{xz}	0.76 MNm/m
Transverse shear	v_x	1.75 MN/m

3. CONSTRUCTION

3.1 Hardware

The hardware components of the LUSET can be subdivided into (i) reaction frame; (ii) load introduction elements; (iii) hydraulic components; (iv) measurement elements; and (v) control system.

3.1.1. Reaction Frame

The reaction frame defines the outer dimensions of the LUSET and equilibrates the reactions of the forces which are applied to the specimen. It consists of an in-plane frame (with outer dimensions of 9.6 x 9.6 m) and an out-of-plane frame that extends approximately 2.8 m off the in-plane frame, see figure 1. The in-plane frame was delivered by the contractor in four equal parts and welded together on site. The out-of-plane frame consisting of hot rolled sections was delivered in several parts and bolted to the in-plane frame. The outer dimensions of the frames as well as the general layout of the stiffeners are indicated in figure 1. Generally, steel of Grade S355J2G3 was used for the reaction frame. Only the eyebars, which are welded to the in-plane frame and connect to the hydraulic actuators, are made of Grade S460N steel.

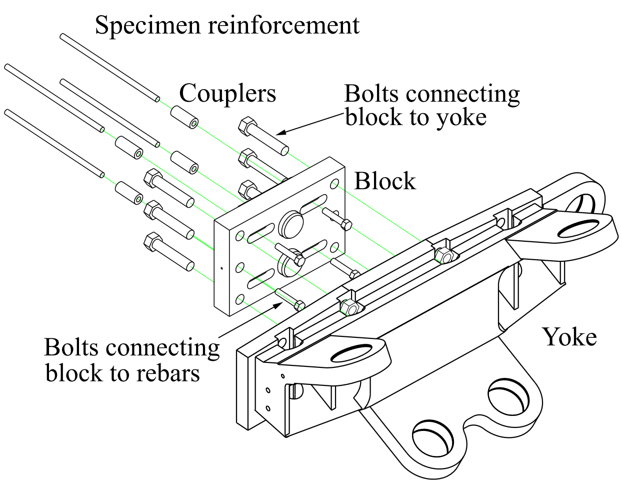

Figure 3. Load introduction system between actuators and specimen; adopted from [1].

3.1.2. Load Introduction Elements

The system of the load transfer between actuators and specimen already mentioned above is illustrated in more detail in figure 3. The actuators apply the forces to the 20 yokes along the four specimen edges, which in turn transfer their forces to 20 blocks. Yokes and blocks are connected by means of 6 preloaded high strength M36 bolts for the transfer of tension forces. The shear transfer between blocks and yokes is ensured by means of two circular shear connectors per yoke (bevelled cylindrical part protruding from outer block edge, corresponding holes in yoke), such that the preloaded bolts are only activated in tension. The connection and force transfer to the reinforcing bars is achieved by means of commercially available reinforcing bar couplers with parallel threads on forged bar ends (BARTEC system), certified to fail outside the thread. Shear forces are transferred to the specimen through shear teeth on the block front side (as well as some dowelling action of the couplers).

3.1.3. Hydraulic Components

The hydraulic hardware components consist of the actuators, the valves and the hydraulic tubing.

Two types of actuators are installed in the LUSET, namely 80 in-plane and 20 out-of-plane actuators. The actuators are built in a very compact way, such that the maximum capacities (see section 2.2) could be achieved with the given space. The actuators are connected to the eyebar at the reaction frame by means of a load pin (see section 3.1.4) and to the yoke on the side of the specimen (see section 3.1.2).

For the actuation of the system, 20 proportional directional control valves are used. The direct-operated valves exhibit extremely high dynamics combined with a high oil flow, such that they reach a frequency response high enough for quasi-instant control of the actuators in the LUSET.

The hydraulic tubing is built in a way such that the LUSET is as universally usable as possible. In case, that tests different from the standard configuration should be performed, bypass pipes to rearrange the connections between actuators and valves are available, as well as mobile linkboxes, rigid links and a tank for maintaining zero force without using a control channel. For more detailed information on the hydraulic components, see [1].

3.1.4. Measurement Elements

Each actuator is equipped with an internal displacement sensor that provides a continuous measurement of the stroke. Additionally, the yokes are instrumented with 20 tilt sensors providing a measurement of the rotation around the y-axis. The information obtained by the aforementioned sensors allows for the calculation of the exact position in space of each yoke and hence the specimen.

The forces applied by the actuators are measured by load pins that are arranged between the actuator fork and the spherical bearing in the eyebar of the reaction frame. Furthermore, making use of the pressure sensors that are located in the chambers of the 20 valves connecting to the actuators, the forces can also be back-calculated by multiplying the pressure to the respective piston area. It should be noted that the latter force does not account for the friction loss in the actuators.

In addition to the aforementioned permanently installed measuring equipment, two independent measurement systems are used in all tests, namely Digital Image Correlation (DIC) and distributed fibre-optic measurements (FO). For a detailed overview of the capabilities and limitations of the independent measurement systems the reader is referred to [2].

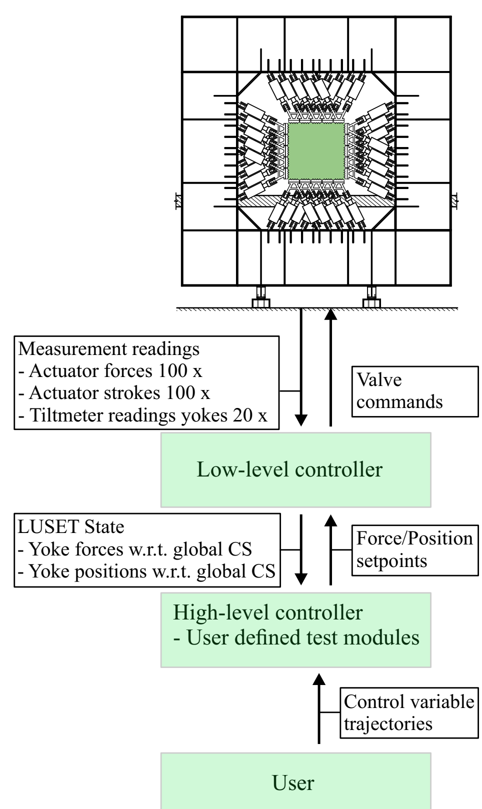

Figure 4. LUSET control software architecture; adopted from [1].

3.1.5. Control System

The control cabinet of the LUSET contains a real time controller with a maximum transfer capacity of 1 GBit and a cycle frequency of 100 kHz which is enabled by an Ethernet based fieldbus GinLink. A Stand-Alone Master CPU board (SAM3) is connected to five IO-Nodes capable of handling more than 800 digital and analog in- and outputs. All machine states are calculated in a real time loop of 1 ms.

The standard control of the LUSET during testing takes place through standard desktop PC's.

3.2 Software

The control software can be distinguished in two parts, namely the low-level and the high-level controller.

The low-level controller is responsible for the synthesis of all individual measurement readings in a unified global reference system and the provision of an interface that translates user defined force and/or displacement targets to suitable control valve commands. Making use of the 100 actuator displacement readings in combination with the 20 tilt measurements per yoke, the kinematics and hence the position in space of each yoke (and associated actuators) can be determined. With this information, the forces exerted by the actuators on the yokes can be transformed to global Cartesian coordinates and summed up to obtain the resulting loads each yoke exerts on the specimen. The low-level controller only allows for the control of a specific group of actuators and not of the global state of the specimen. For the definition and execution of the tests, hence the control of the global state of the specimen, the high-level controller is used.

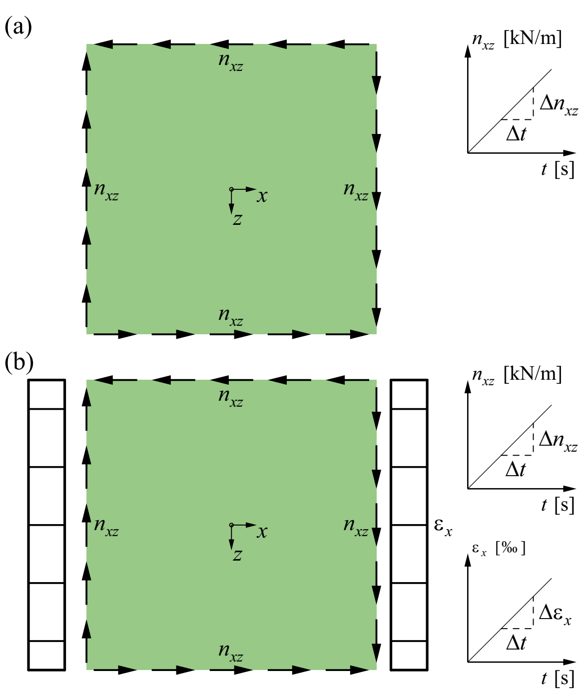

Figure 5. Load path of pilot tests: (a) PT1-PT3; (b) PT4; adopted from [1].

The high-level controller is a position-based cascade control that employs individual position controllers for all the actuator groups of a given machine configuration. The conditions that an experimentalist wants to impose on a specimen are represented by a collection of generic variables that are achieved by controlling the position of the actuator groups. These generic variables can be either imposed deformations (kinematic restraints), forces or a combination thereof. For further information regarding the high-level controller, the reader is referred to [3].

4. PILOT TESTS

In the framework of the commissioning of the LUSET, a pilot test series consisting of four tests (PT1-PT4) was conducted in order to verify the basic verify the basic functionality of the facility. PT1, PT2 and PT3 were tested under pure membrane shear (see figure 5a) and PT4 was tested under membrane shear with an imposed longitudinal strain in x-direction (see figure 5b).

The pilot tests were loaded up to failure with an applied loading ramp of $\Delta n_{xz}/\Delta t$ = 20 kN/min.

Minor problems in the control strategy were identified during tests PT1 to PT3 and were subsequently corrected prior to the execution of test PT4. Test PT4 provided a validation of the modifications made in specific and of the overall control strategy in general. The pilot test series was therefore a success and more than 30 tests have since been carried out up to the time of writing this paper (see e.g. [4], [5]).

5. TESTING POSSIBILITIES

5.1 General

In addition to tests subject to the standard test configuration, where the specimen is subjected to homogeneous loading along its four edges, the modular concept of the facility enables an array of different test configurations and/or setups which are summarised in the following two sections.

5.2 Alternative Test Configurations

By rearranging the connections between actuators and control valves, hence changing the machine configuration, different non-homogeneous loading types can be achieved. An example of such a non-homogeneous loading type is a panel test with in-plane shear loading and an imposed longitudinal strain with a gradient along the specimen's edge, similar to test PT4 described in section 4 and illustrated in figure 6.

5.3 Alternative Test Setups

The yokes are designed such that specimens with out-plane dimensions in excess of what the standard blocks can facilitate can be tested. This enables one to one tests on a large range of structural types such as for example retaining walls with footings, columns with concrete dimensions.

By using suitable connection devices other than the blocks that were discussed in section 3.1.2 and illustrated in figure 3, alternative materials that do not contain conventional reinforcement can be tested such as Fibre or Textile Reinforced Concrete.

Additionally, the control architecture allows the execution of so-called hybrid tests where the physical specimen is part of a numerical structure, this way allowing experimental investigations on the system level and hence investigations of the deformation capacity of entire structures.

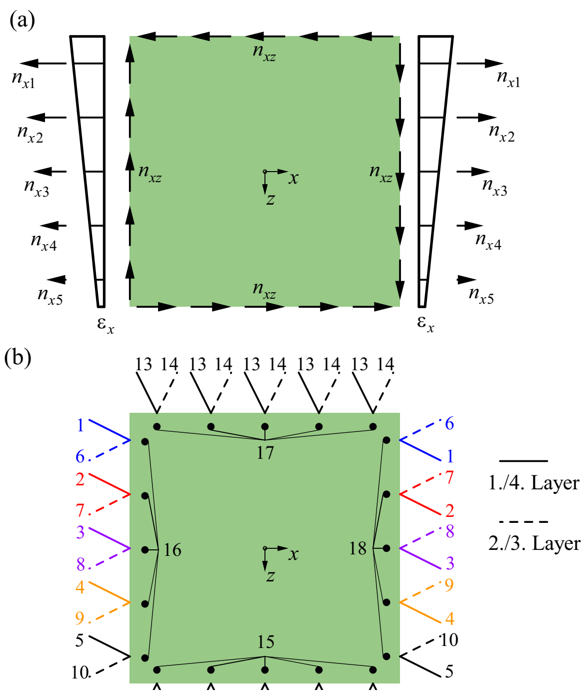

Figure 6. Non-homogeneous panel test in the LUSET, with shear loading and imposed longitudinal strain with a gradient: (a) loading; (b) machine configuration; adopted from [1].

6. SUMMARY

A new testing facility to investigate the load-deformation behaviour of large-scale reinforced concrete shell elements has been developed at ETH Zurich: The Large Universal Shell Element Tester (LUSET). The LUSET enables the testing of reinforced concrete elements with in-plane dimensions of 2.0 x 2.0 m and a variable thickness of up to 0.38 m. This paper presents a description of its capabilities and limitations, the hardware and software components and its modular concept and associated testing possibilities.

Acknowledgements

The LUSET was inspired by two testing facilities at the University of Toronto, whose loading possibilities it combines at a larger scale: The Shell Element Tester (SET) [6], [7] and the Panel Tester (PT) [8]. The authors would like to thank Profs. Evan Bentz and Michael Collins for providing them with in-depth information of the testing facilities and procedures at the University of Toronto, which were highly valuable for the design of the LUSET at ETH Zurich.

A special thanks goes to Prof. em. Peter Marti, who provided his original drawings of the SET and inspired the concept of the LUSET.

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