

# EXPERIMENTAL MEASUREMENTS OF STRUCTURAL DISPLACEMENT DURING HYDROGEN VENTED DEFLAGRATIONS FOR FE MODEL VALIDATION

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## ABSTRACT

Vented deflagration tests were conducted by UNIPI at B. Guerrini Laboratory during the experimental campaign for HySEA project. Experiments included homogeneous hydrogen-air mixture in a 10-18% vol. range of concentrations contained in an about 1 m<sup>3</sup> enclosure, called SSE (Small Scale Enclosure). Displacement measurements of a test plate were taken in order to acquire useful data for the validation of FE model developed by IMPETUS Afea. In this paper experimental facility, displacement measurement system and FE model are briefly described, then comparison between experimental data and simulation results is discussed.

## 1. INTRODUCTION

UNIPI has designed a generic experimental enclosure suitable for investigating vented hydrogen explosions in installations such as gas cabinets, cylinder enclosures, dispensers and backup power systems. The enclosure consists of two solid steel frame connected between themselves to form the entire frame which supports the main components of the measurement system (pressure sensors, structural response gauges). The main frame can be covered with various combinations of walls, doors, internal congestion and vent panels. The experimental setup allow researchers to study the effect of internal obstacles (bottles), construction materials (including structural response), and the effect of mitigating hydrogen deflagrations by means of various venting devices. The complete description of test facility is reported in the HySEA Report D2-03-2017 [1]. Figure 1 shows a schematic view of the instrumentation for the tests in the small-scale enclosure.

A total amount of 76 tests were performed in which the variables under investigations were hydrogen concentration, vent location and type, ignition location, internal obstacle configuration. Data of overpressure and test plate displacement were acquired during the deflagration. The complete resume of results, including Pressure-Time and Displacement-Time histories for each test can also be found in the HySEA Report D2-03-2017 [1].

IMPETUS has developed a finite element model to simulate the structural response of the test plate, in particular to calculate the displacement suffered due to overpressure. Two thicknesses of the plate were tested, namely 2 and 5 mm. The first suffered plastic deformation after few tests affecting the following measures. For this reason it was replaced with a thicker one and IMPETUS model is based on 5 mm thick plate.

Results from experimental measurements and numerical simulation have been compared to validate the FE model. Starting from the comparison with one representative test, the FE model has been updated to be representative of a larger set of applied loading.

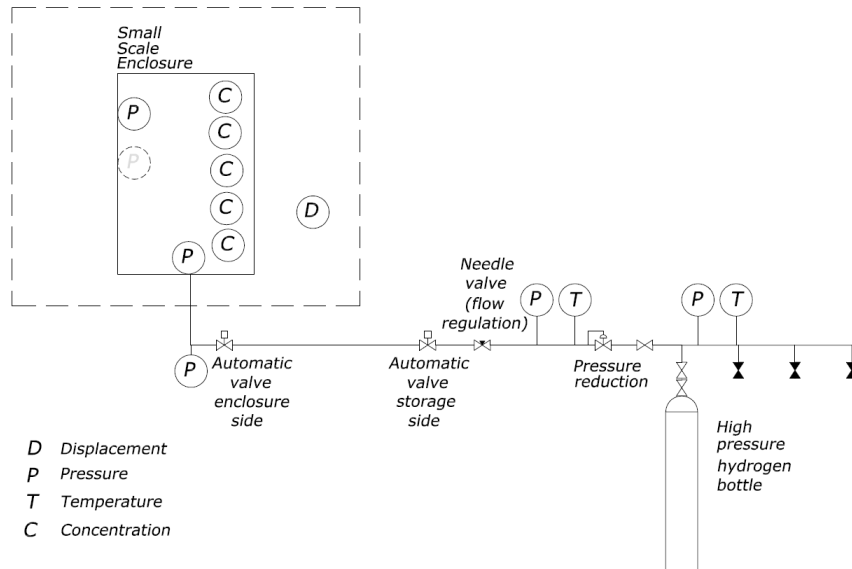


Figure 1. Small Scale Enclosure experimental setup

## 2. EXPERIMENTAL MEASUREMENTS

The Front side of the SSE hosts test plates which can alternatively be positioned in two locations: the lower and the upper side, see Fig.2(a). The first part of the experimental campaign (tests from TP1 to TP20) was performed measuring the displacement using a mechanical method, a so called antenna, Fig.2(b). This method is very simple but has poor precision and it can reveal only the maximum displacement suffered by the plate. The remaining part of experimental measurements was executed using a Keyence laser sensor IL-S025, Fig.2(c), [2]. In addition to the maximum displacement occurred, the laser can record the displacement-time histories during the deflagration. Displacement-time histories plots for each tests performed with laser can be found in HySEA Report D2-02-2017, annex 2. [1]

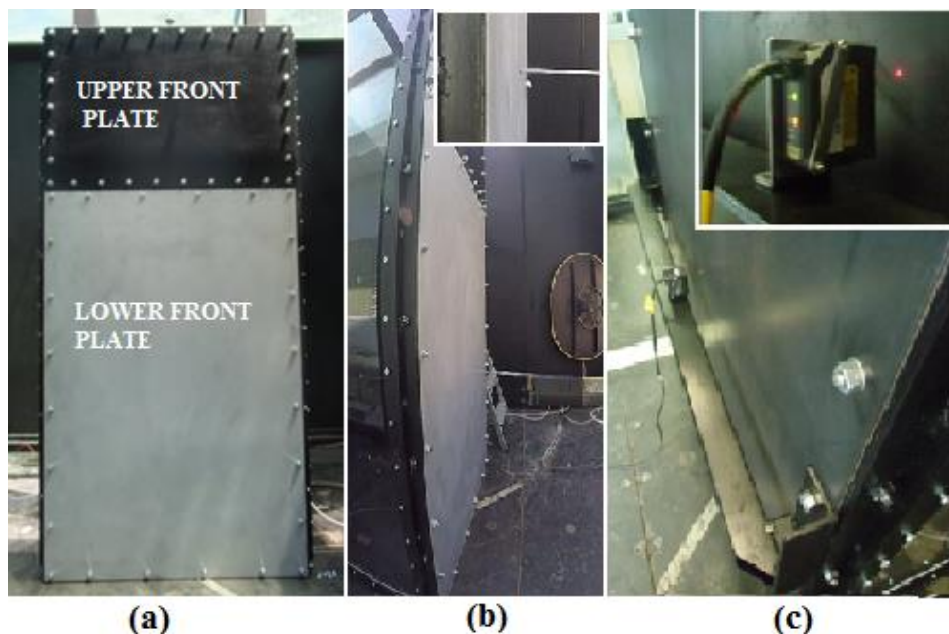


Figure 2. Small Scale Enclosure (a), Mechanical sensor (b), Laser sensor (c)

The maximum value of overpressure generated during the deflagration depends on test configuration (hydrogen concentration, vent type, vent location, ignition point, internal congestion). The expected behaviour of the test plate is that the maximum displacement registered is proportional to the maximum overpressure occurred. The plot in Fig.3 represents the measurements operated with mechanical method. The three circled spots are the first measurements. Notice that spots TP1 and TP2 gave a proportional response to pressure applied (left side line) while from TP3 results follows a line with a lower slope (right side line). This behavior was both affected by a new equilibrium position of the plate which is pulled toward the center and kept in the new position by the friction of the bolted connection, and from the plasticization of the plate itself. The first of the two contribution was periodically eliminated by the operation plate removal and reinstallation during the checking and maintenance operation of the internal volume, while the plasticization of the plate affected all the following tests.

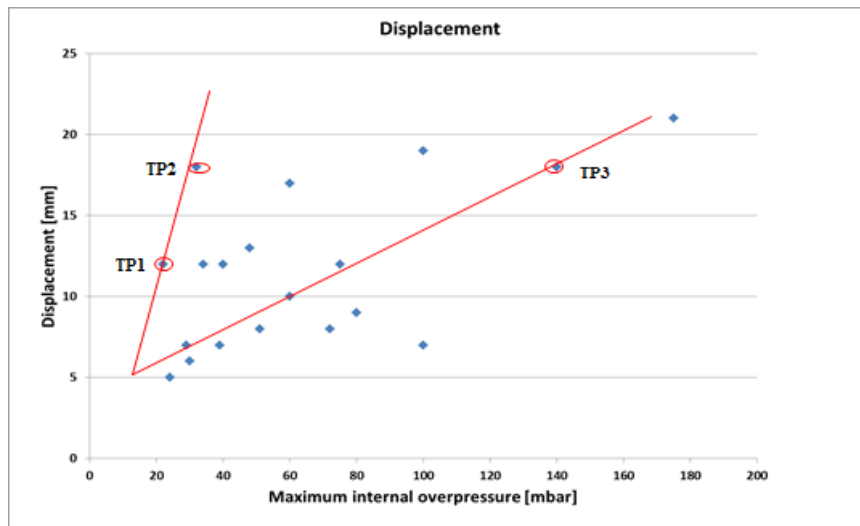


Figure 3. Maximum displacement vs. maximum recorded pressure

Taking into account the results from the first twenty tests it was decided to modify the experimental setup by substituting the test plate with a thicker one, namely 5 mm, that allows an elastic response to the applied internal pressure. Furthermore the so called antenna was replaced with the laser sensor able to measure with very high precision the displacement time history. From test TP21 to TP29 the sensor was placed in the center of the lower test plate. In tests where higher internal overpressures occurred the sensor saturation was reached. For this reason the laser was moved along the centerline of the lower plate, as in particular measurements were taken at 91.3 cm ( tests TP30 to TP33) and 111.45 cm (tests TP34 to TP36 and TP45 to TP52) from the floor, as indicated in Fig.4.

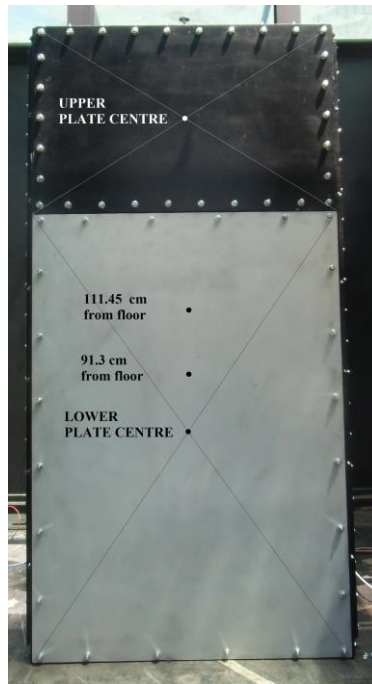


Figure 4. Displacement laser sensor locations

A resume of facility's configuration about the displacement measurement is in Tab.1.

Table 1. Experimental set up for displacement measurements.

Measurement method	Test plate	Plate thickness [mm]	Sensor location	TEST # (interval)
Antenna	Lower	2	Plate centre	TP1-TP20
Laser	Lower	5	Plate centre	TP21-TP29 TP65-TP70
			91.3 cm from floor	TP30-TP 33
			111.45 cm from floor	TP34-TP36 TP45-TP52
	Upper	5	Plate centre	TP37-TP44 TP53-TP64 TP71-TP76

Fig.5 shows the maximum measured displacement in function of the maximum overpressure acquired by transducer  $P_{side}$  for the three different locations. The 5 mm thick plate works in the elastic field but the results are quite far from being aligned along a theoretical straight line. Data scattering from the proportionality between maximum displacement and overpressure could be explained by the dynamic nature of the deflagration: overpressure measurements are taken at two locations not absolutely representative of the pressure applied to the lower plate. In fact, pressure transducer called  $P_{bottom}$  is situated on the floor, while the other one called  $P_{side}$  is on the upper part of the SSE back wall, Fig.6.

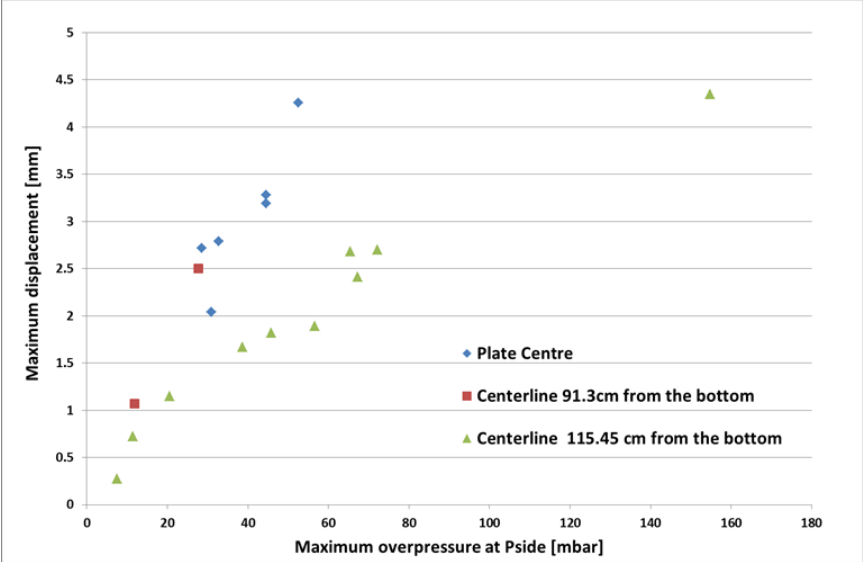


Figure 5. Maximum displacement vs. maximum recorded pressure at  $P_{side}$

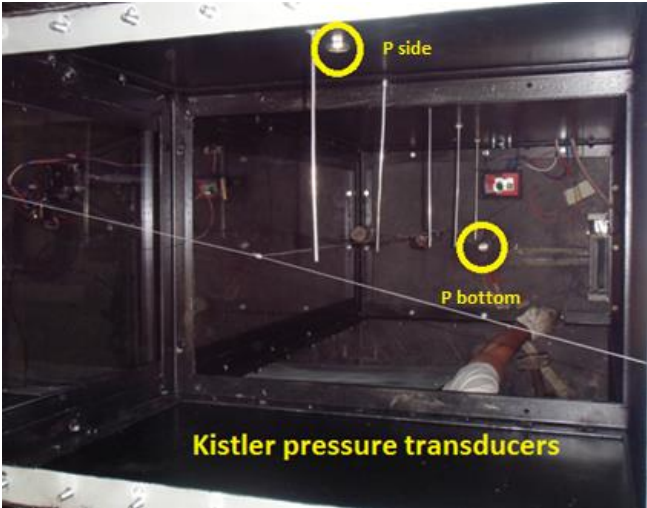


Figure 6. View from above the SSE: Top vent area and pressure transducers locations

To minimize the uncertainty due to the difference between the applied overpressure on the target plate and the recorded pressure in one of the two locations, the displacement was measured in the center of the upper front plate whenever the venting area used was the top one, Fig.5. This displacement measurement location is directly opposite to the location of the pressure transducer  $P_{side}$ . In this way

the pressure applied to the plate could be related to the pressure measurement with more precision. The following Fig.7 shows the result of the maximum displacement measured in the center of the upper front plate as a function of the maximum overpressure measured at Pside. Can be noticed that data scattering from the straight line is minimized.

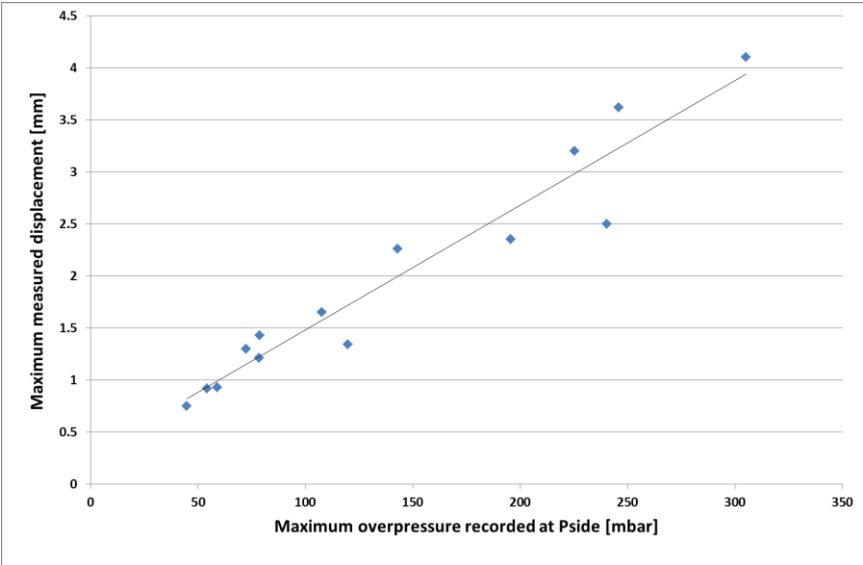


Figure 7. Maximum displacement measured in the Upper front plate center vs. maximum recorded pressure at Pside

In tests where FIKE panel is used, the maximum internal overpressure occurs at the vent opening. Therefore the displacement measurements is taken before the dynamic evolution of deflagration which leads to pressure gradients between different volume: as a consequence plate structural response will be proportional to the applied pressure. Fig.8 confirms the expected behavior being the spots located on an imaginary straight line.

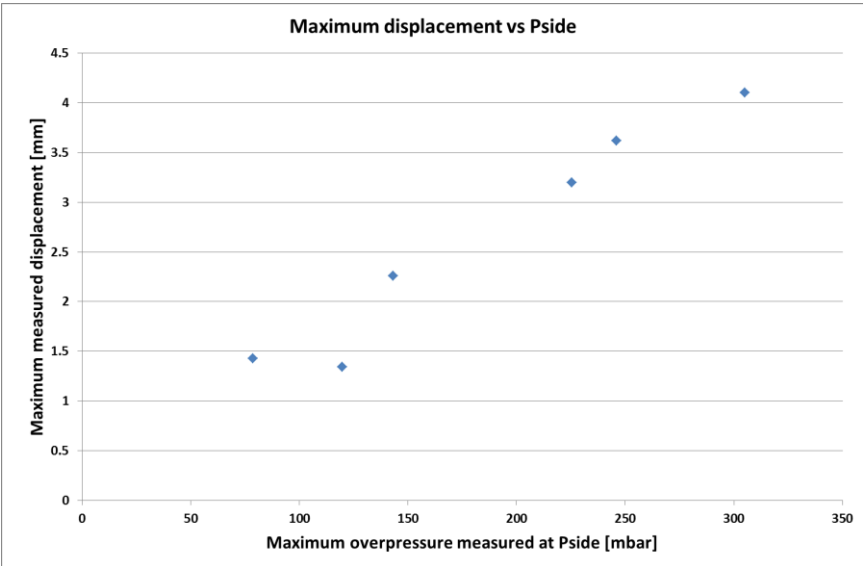


Figure 8. Maximum displacement measured in the Upper front plate center vs. maximum recorded pressure at Pside for tests performed with a FIKE vent

The absence of relevant pressure gradients inside the SSE is revealed also by the small difference in the measurements of the two pressure transducers, Fig.9. This phenomenon does not occur when tests are performed using plastic sheet vent and the displacement measurements is taken after the development of dynamic stage of the deflagration.

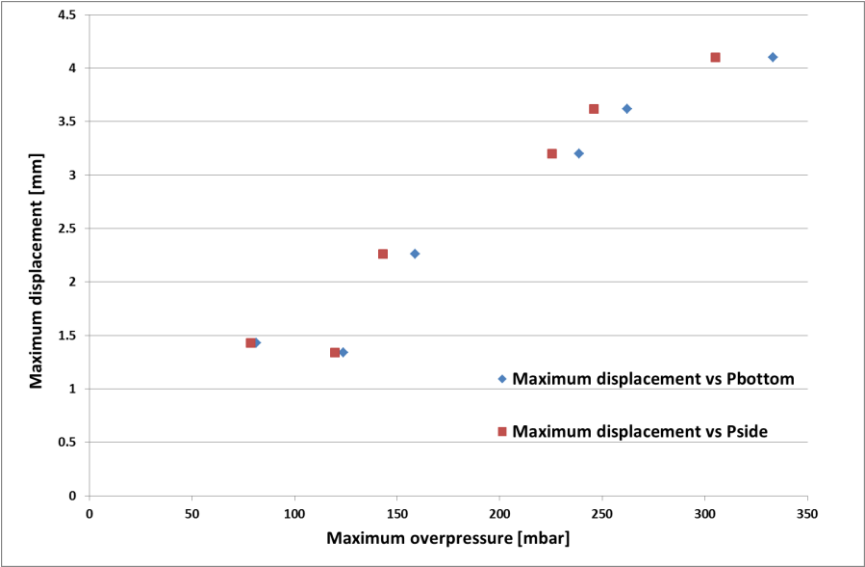


Figure 9. Maximum displacement measured in the Upper front plate center vs. maximum recorded pressure at Pside and Pbottom for tests performed with a FIKE vent

Tests from TP37 were characterized by tightening the bolts of the test plate with a determined torque. Fig.10. shows that experimental results are not appreciably affected by the different magnitude of pre-torque. However this parameter is fundamental for FE in modelling the plate's bolted connection to the frame. Three different values of tightening torque were tested: the reference one was set at 50 Nm, the other two cases were 20Nm and 80Nm.

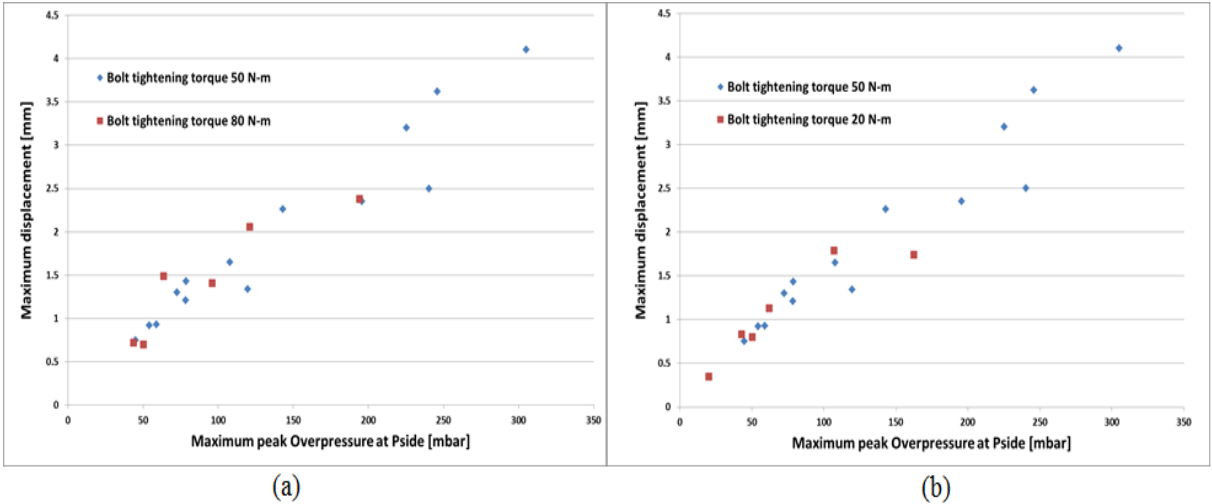


Figure 10. Maximum displacement measured vs. maximum recorded pressure at Pside for different tightening torques

### 3. FE MODEL

A finite element model was made of the upper side wall of the enclosure where the displacement measurement, that showed the best accuracy, was done. The explicit, non-linear finite element software IMPETUS Afea Solver was used for the simulations. The model consists of 5 parts, see Fig. 11:

- the main side-wall test plate (5 mm)
- the main rectangular frame consisting of 4 mm thick L-profiles with outer flange dimensions 50 mm (L50x4mm)
- 30 bolts with 10 mm OD
- 30 corresponding nuts
- 30 corresponding washers

All parts were modelled with the quadratic solid elements of IMPETUS Afea Solver. The rear end of the main frame was constrained, Fig.10.

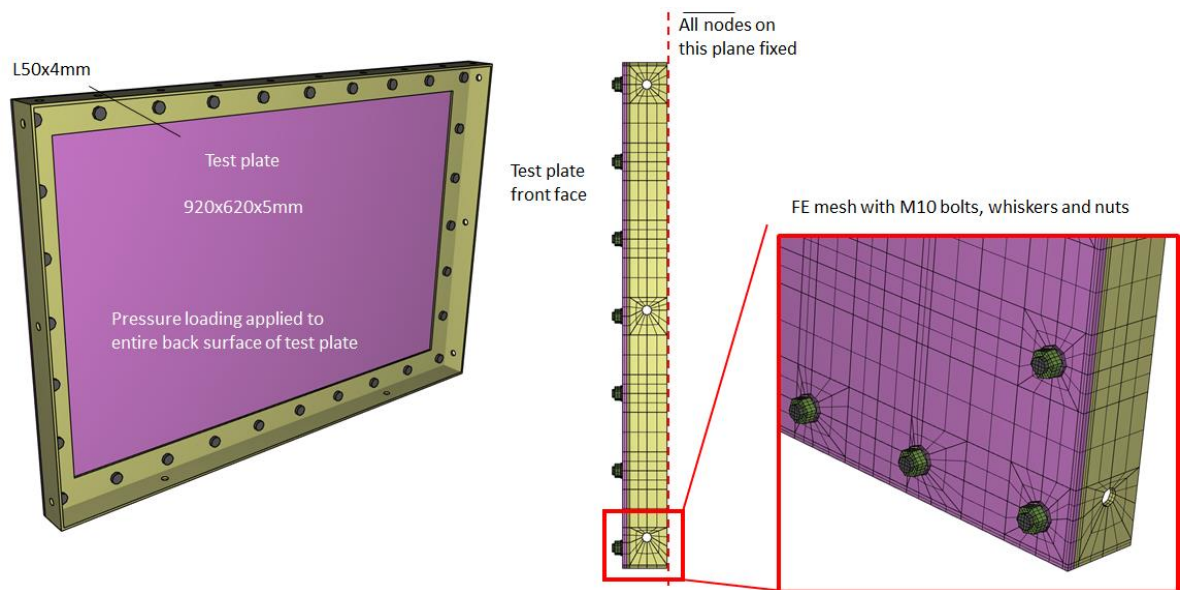


Figure 11. FE model overview - back face with boundary conditions and load specification

This assumption leads to a higher stiffness of the frame than in reality but is acceptable for small pressure loadings occurring for the current experimental test program. All materials were modelled as a typical S235 steel, even the bolts, using the following material from the material library of IMPETUS Afea Solver: “S235\_DNV-RP-C208\_DNV(2013)\_<0,16]\_ISO\_YVM\_QS”. The response of the parts is elastic during the event so the non-linear properties of the material model is of no importance. The general contact algorithm of IMPETUS Afea Solver was activated for all parts of the model. A Coulomb friction coefficient of 0.2 was used between all parts.



The first selected test for validating the numerical code was TP37. In Tab.2 the experimental set up for this test is resumed. Pressure-time and displacement-time histories are available in HySEA report D2-02-2017, annexes 1 and 2 [1].

Table 2. Experimental set up for test TP37.

Test Id	Average H <sub>2</sub> Conc.	Vent location	Vent type	Ignition location	Obstacle conf.	Test plate #	Test plate thick.	Displac. Measur. method	Displac. Measur. Location
TP37	14.1%	Top vent	FIKE Vent 3	Bottom	3 bottles	(2)	5 mm	Laser	Plate centre

The simulation was done in two steps. In Step 1 the bolts were pre-loaded to an axial stress of 200 MPa to represent the pre-torque. In the second step, the pressure-time curve obtained from experimental Test TP37, was imported and used to load the complete rear surface of the test plate, Fig. 10. The curve was used as is, but the time axis was shifted so that t=0 in the model represents the time when a significant overpressure signal was first registered.

The relation between axial stress and pre-torque was estimated from EN-10190. By using a pre-stress of 200 MPa we are assuming that the pre-torque is between 15 and 25 Nm.

From the simulation of Step 2 we obtained the displacement field of the test plate as function of time. The displacement-time curve of the centre of the test plate was then extracted. Fig. 12 shows a contour plot of the displacement field of the test plate at time t=0.102 s.

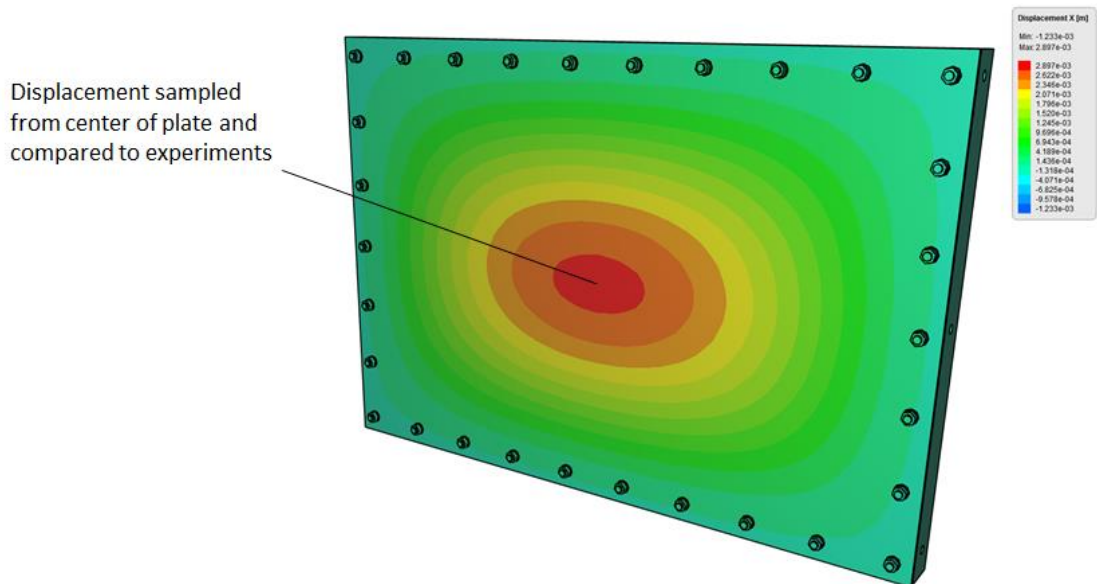


Figure 12. Contour plot of displacement of front face of test plate at time t=0.102 s

#### 4. COMPARISON BETWEEN DATA AND FE MODEL

The obtained curve was then compared to the displacement-time curve obtained from experiment TP37 at the same location of the test plate, see Fig.13. We see that from the experiments we get a maximum displacement of 3.2 mm, whereas the model gives 2.9 mm.

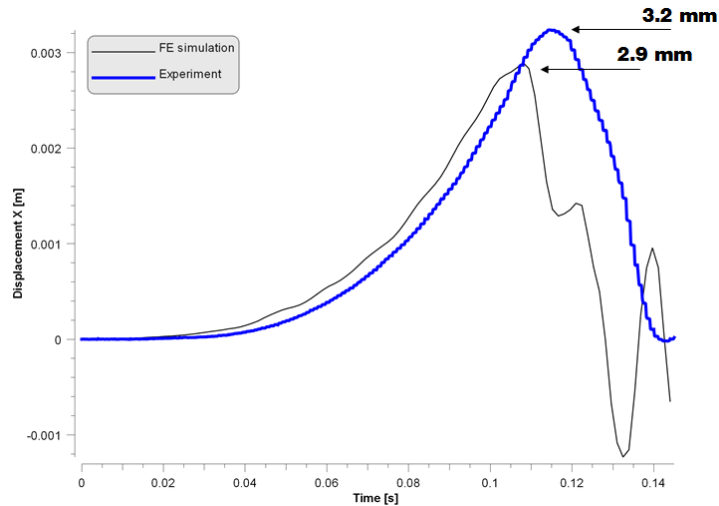


Figure 13. FE simulation results, Test T37 – simulated vs measured displacement of plate center

In order to compare the model behaviour with a larger set of experimental data, simulations were done with a smooth ramp up of the pressure loading following the function of Fig.14.

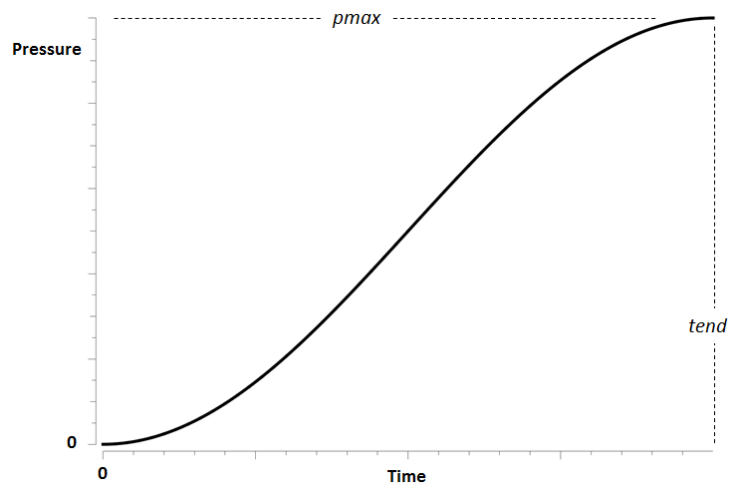


Figure 14. Smooth ramp-up function for near quasi-static analysis

The parameters  $p_{max}$  and  $t_{end}$  were varied on three levels and all combination simulated. The levels for  $p_{max}$  were (100, 200, 300) [mbar] and the levels for the load duration  $t_{end}$  were (0.02, 0.03, 0.04) [s]. As seen from Fig.15, the model behaviour is well within the experimental scatter.

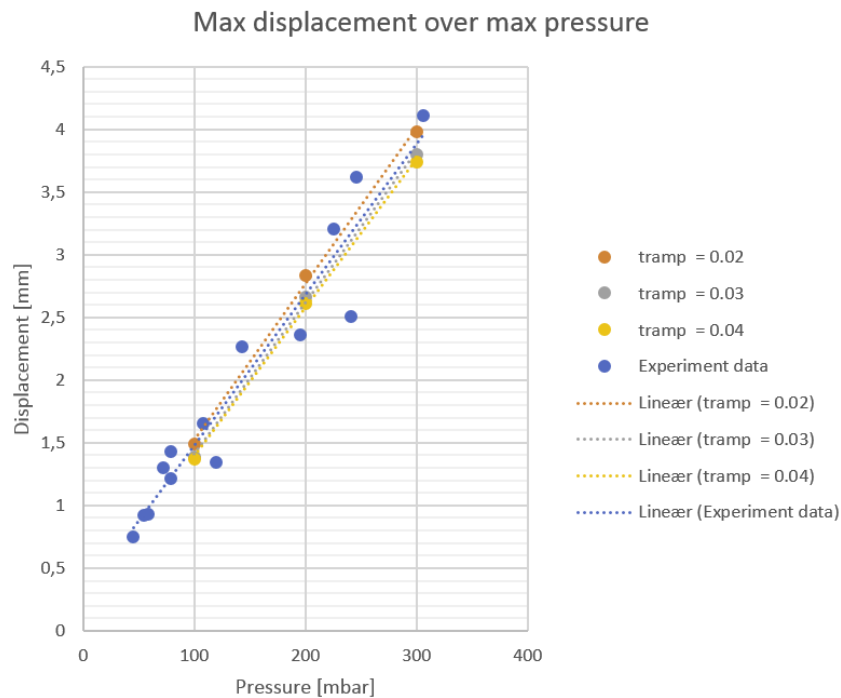


Figure 15. : Center plate peak displacement vs peak pressure, FE simulation vs experiment

## 5. CONCLUSIONS

A series of 76 deflagration tests with an hydrogen-air homogenous mixture has been performed by UNIPI. With the aim of investigating the effect of overpressure on the facility's wall, the displacement of a test plate was measured. In order to perform an accurate measure the following expedients had to be taken:

- Substitution of 2 mm thick test plate with a thicker 5 mm plate to avoid metal plasticization that can affect the following measures;
- Placing the measurement in a representative position with respect to pressure transducer in order to ensure that the measured pressure is representative of the actual pressure applied on the test plate.

Regarding the validation of numerical model, there are a number of uncertainties between the model and the experiments. The mesh density, element type and boundary conditions appears to represent this experimental test set-up well. For larger pressure loads involving possible plasticity and material failure it would have been necessary to use more representative material models and possibly a finer mesh.. Furthermore the pressure signal is not sampled directly at the location of the displacement measurement introducing an error whenever the dynamic of the deflagration causes spatial differences inside the enclosure.

Next experimental campaign that UNIPI ,with help of IMPETUS and FIKE, planned to perform, will provide additional data useful to validate FE model in a bigger variety of conditions and to improve his predictive capacity.

## **6. ACKNOWLEDGEMENTS**

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## **7. REFERENCES**

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