# A Comparison of Strain Gauge Measurements and FEA for a Confined Channel Geometry Subjected to a Hydrogen-Air Mixture Explosion

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**Abstract**

Using finite element analysis for rapid dynamic loads without validation of the results can lead to major miscalculation, thus making it necessary to examine the accuracy of the software. The structural response from a hydrogen-air mixture explosion in a confined channel is investigated with experiments and numerical methods. The channel measures 1000 mm in length, with an inside diameter of 65 mm, and 15 mm thick transparent polycarbonate sidewalls. Hydrogen and air were released into the channel and ignited. Four Kistler transducers record the internal pressures. A biaxial HBM rosette strain gauge was bonded to the polycarbonate sidewall, used for recording strains during the explosion experiments, where von Mises stresses were calculated from these recordings. The channel was then idealized as a computer-aided design model in the engineering software SOLIDWORKS. By utilizing the pressure data from the experiments and creating a four-pointed loading curve, finite element analysis was applied for obtaining numerical von Mises stress results. Comparing the experimental and numerical results of von Mises stress show a variation of 4.9%.

*Keywords: Structural Response, Finite Element Analysis, Strain Gauges, Explosions*

## 1. Introduction

Hydrogen can be a key contributor in the transition to renewable energy, especially in the process and transportation sectors. As hydrogen is an efficient energy carrier with a zero emission of $CO_2$ during combustion, it will be an important resource for solving current environmental challenges. Despite this benefit, there is also a downside; hydrogen is a highly flammable substance with an associated risk of fire and explosion. An accidental explosion can have immense consequences such as economic losses, personnel injuries, or in worst case fatalities. With the following dangers of hydrogen, precautionary measures in engineering structures and designs transporting or storing hydrogen must be taken into consideration. This should be prioritized to limit the potential destructive outcome in case of an explosion.

A blast wave from a hydrogen explosion inside a confined space will be of a rapid phenomenon, combined with high pressures and energies [1]. As the explosion's subsequent waves will reflect inside confined spaces such as channels or tunnels, it can be challenging to numerically simulate the explosion and the structural response simultaneously as a coupled occurrence. The normally applied approach is using decoupled numerical simulation, where the structure is modeled in a computer-aided design (CAD) software and furthermore simulated with a less complex explosion incident using the finite element method (FEM). The loading scenario in these simulations are often simplified to a curve in a triangular shape for pressures, forces, or velocities, where this data can be obtained through experiments, distinct numerical simulation or using empirical formulas [2-4]. However, this process requires certain assumptions for both the CAD model and the loading curve. It is hence necessary to verify the accuracy of the results from finite element analysis (FEA) software. This is especially important when performing FEA with complex loading situations such as explosions or other rapid dynamic loads.

In this paper, the occurring von Mises stresses on a 1-meter-long alloy steel channel exposed to a hydrogen-air mixture explosion is analyzed, with physical experiments using biaxial rosette strain gauges, and using decoupled numerical simulation. It is also beneficial to use von Mises stresses as a reference for comparison, as the strain gauge can measure biaxial stresses under complex explosive loads. Furthermore, the aim of this study is to verify if the simulation results from the commercial computer-aided engineering (CAE) software SOLIDWORKS[1] will be similar to the strain gauge measurements, and if the software is suitable to use for these kind of loading circumstances. This information will be helpful for engineers designing structures which should withstand explosive loads.

The experiments were conducted in collaboration with another research project at the University of South-Eastern Norway, where the physics of the explosion and the deflagration-to-detonation transition (DDT) was investigated [5]. This paper will focus on the structural behavior of the experimental rig.

## 2. Experimental setup

The experimental rig consisted of an alloy steel channel with an inside length of 1000 mm and a cross section of 116x65 mm. The channel was closed at the left end, and open at the right end. On its sidewalls, it was fitted with 15 mm thick transparent polycarbonate sheets fastened with M8 bolt connections, tightened to 15 Nm. Two steel plates were mounted at the right end for structural stability. Recording of pressure data were done by four Kistler pressure transducers (P1-P4) with a sampling rate of 100 kHz, mounted to the channel with a spacing of 250, 450, 650 and 850 mm relative to the left side of the channel, see Fig. 1. The center of the channel was filled with 40 cylinders, with an intent to create a turbulence for the gas and incite a DDT.

For strain gauge measurements, an HBM 3/120 RY81 Rosette with three measuring grids and a resistance of 120 Ω was used. The gauge factor was 2.03 for all measuring grids, with a transverse sensitivity of 0.2 % for gitter A and C, and a 0% sensitivity for gitter B. HBM states that the measurement uncertainty for stress measurements can be up to 6% [6]. The strain gauge was wired in a half bridge to three channels to an HBM Spyder 8 data acquisition module (DAQ), with a sampling rate of 4.8 kHz. The DAQ module was connected to a computer running the catman[2] measuring software. Catman was set-up to calculate von Mises stresses. The strain gauge was bonded to the backside polycarbonate sheet, see Fig. 2.

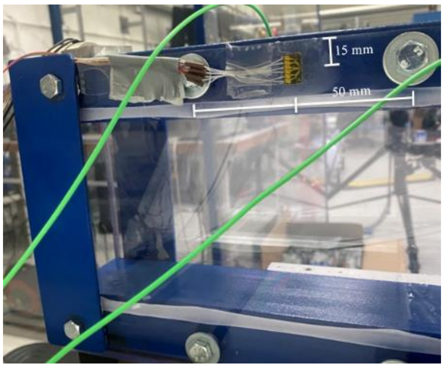


Figure 2: Strain gauge location

By initiating a spark to the mixture of hydrogen and air in the channel, a following explosion would occur.

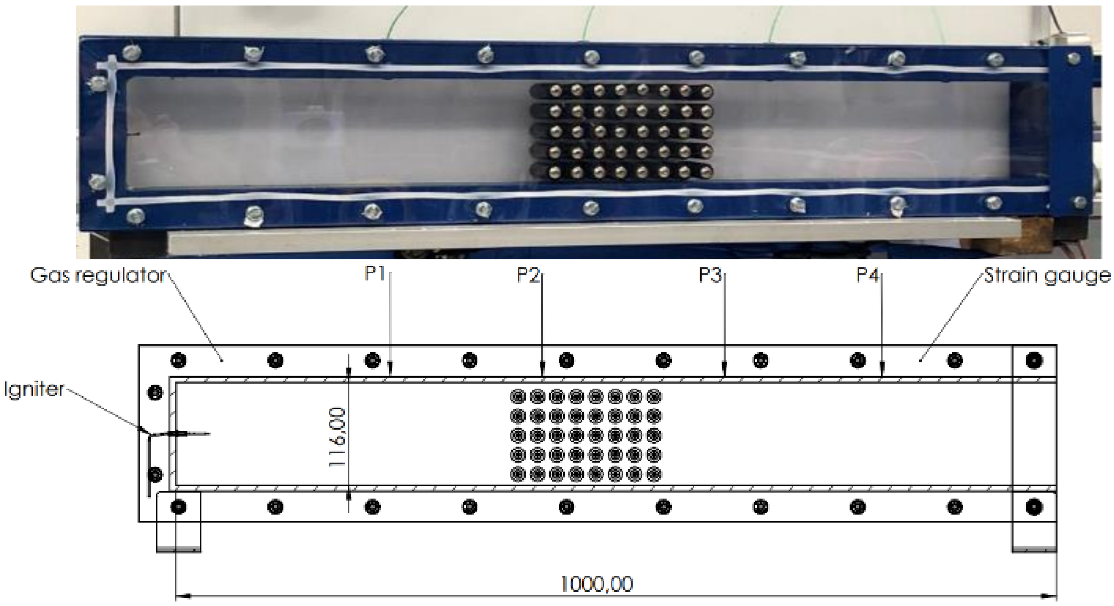


Figure 1: Photo and schematic of the channel

[1] SOLIDWORKS by Dassault Systèmes
[2] catman Data Acquisition Software by HBM

The transducers recorded the achieved explosion pressures, which would later be used in the FEA. A more in-depth explanation of the initiating explosion procedure is given by Henriksen et al. [5]. In total, four experiments were conducted.

Furthermore, as the pressures recorded from transducer P4 are the most interesting (since the strain gauge is bonded in this area), this pressure data will be used in the FEA analysis. A table showing the P4 transducer peak pressures can be seen in Tab. 1. The pressure curve from Exp. 2 for P4, which was the highest achieved pressure, is shown in in Fig. 3.

Tab 1: Peak pressures from P4

| | **Peak pressure recorded by transducer P4 [MPa]** |
|---|---|
| Exp. 1 | 0.42 |
| Exp. 2 | 1.21 |
| Exp. 3 | 0.58 |
| Exp. 4 | 1.19 |

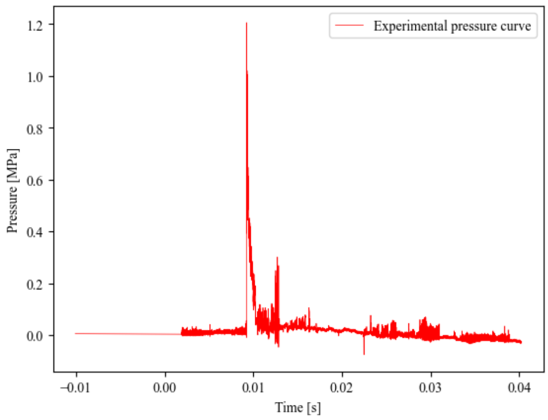


Figure 3: Pressure curve from Exp. 2 P4 transducer

**3. Numerical setup**

The experimental rig was modeled in SOLIDWORKS and simplified to a 260 mm long symmetric model relative to the open end of the channel. For meshing the model, a blended curvature-based mesh with a minimum element size of 3 mm and maximum element size of 20 mm was used. The model consisted of a total of 24739 four-nodal tetrahedral elements and 41289 nodes. 98% of the mesh had an aspect ratio lower than 3.

Using the SOLIDWORKS Connection feature, six M8 bolts with a pretension torque of 15 Nm were added to the model. Contact feature was used to simulate the physical contact of the channel, steel plate and the polycarbonate sheet. The model and the mesh can be seen in Fig. 4. As the highest explosion pressures were recorded in Exp. 2 (see Tab. 1), the simulations were based of this data.

Furthermore, it was used symmetry conditions to enforce boundary conditions.

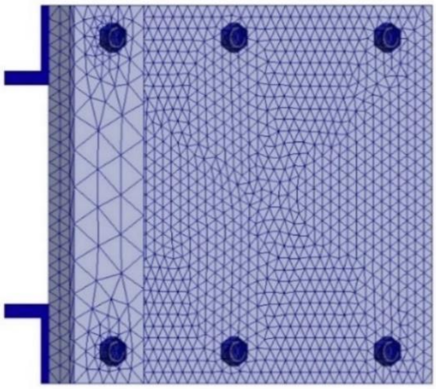

Figure 4: Meshed FEA model

By utilizing the peak pressures recorded by P4 during Exp. 2, the loading pressure curve was simplified to a four-pointed triangular-shaped curve relative to time, see Fig. 5. The pressure was uniformly placed on all inside surfaces of the model. Furthermore, the simulation was run as a non-linear dynamic study with 59 steps with an initial time increment of 0.001 sec., starting at 0 sec. and ending at 0.012 sec. The simulation study was conducted up to a time period of 0.012 seconds due to the fact that the explosive blast pressures from Exp. 2 diminish to nearly 0 MPa at the end this timeframe.

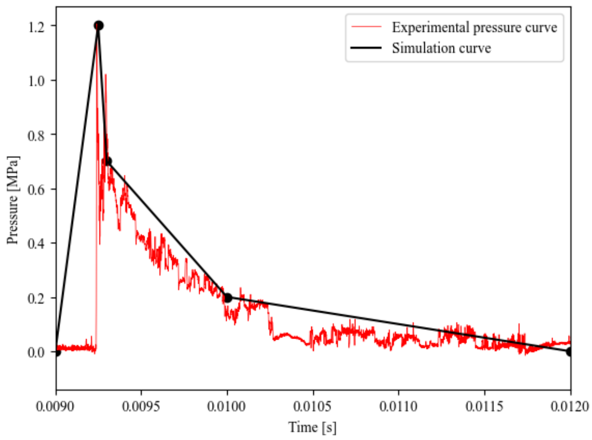


Figure 5: Simulation loading curve compared with Exp. 2 P4 pressure curve.

**4. Results**

This section is divided into three subsections: experimental results, numerical results and comparison of the results.

*4.1. Experimental results*

The maximum achieved internal explosion pressure from P4 is shown in Tab. 1, as this is the area of the strain gauge location. The measured von Mises stresses results from the experiments can be seen in Fig. 6.

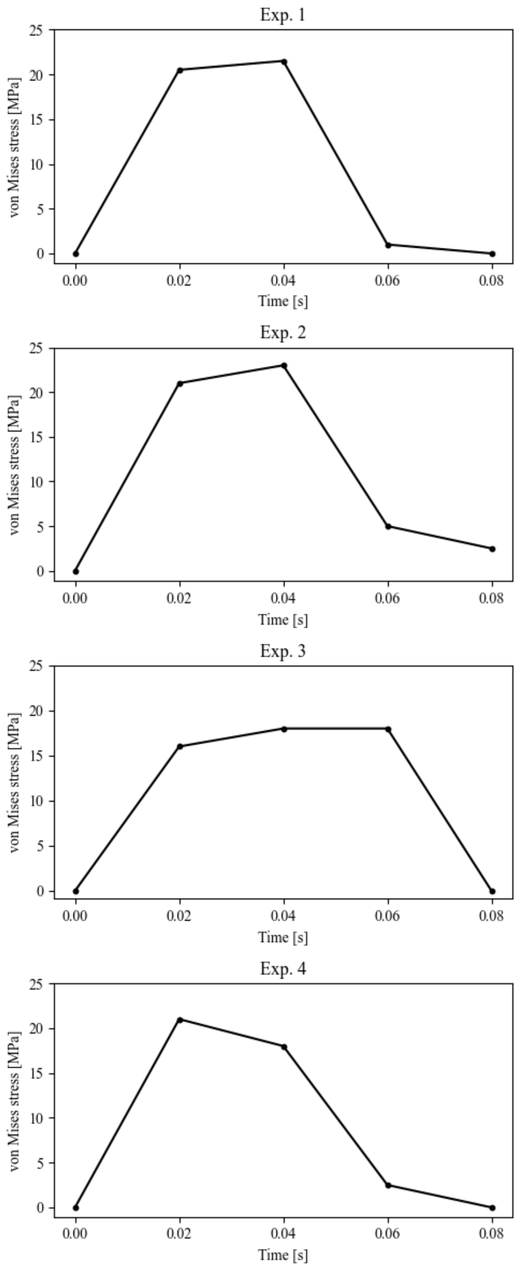


Figure 6: Strain gauge measurement results

The values seem to be similar in their maximum von Mises stress, alternating between 19 MPa and 22 MPa. The DAQ recorded five data points of stress for the experiments. This can be seen in the x-axis presenting time, starting at 0 sec. to 0.08 sec. The data points have a spacing of 0.02 sec.

Data such as hydrogen flow, ignition timing/position or if DDT occurred is beyond the scope of this paper, and thus not emphasized, nor presented.

### *4.2. Numerical results*

Numerical results from the non-linear dynamic SOLIDWORKS simulation achieved a peak stress of 22.2 MPa in the same area as the strain gauge was located. This happened in simulation step 49 at 0.009 sec simulated time., which was the time of the highest loading pressure. The scaling of time in the dynamic response is different from the von Mises experimental results, as the loading pressure curve and simulation are based on data from the pressure transducer P4, see Fig. 7. In Fig. 8, the FEA stress contour plot of the polycarbonate plate model is presented.

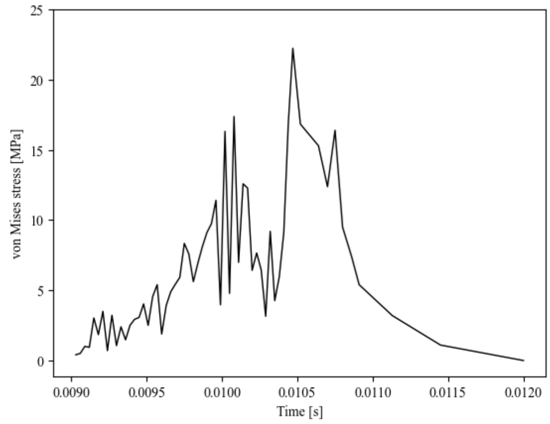


Figure 7: Structural simulation response

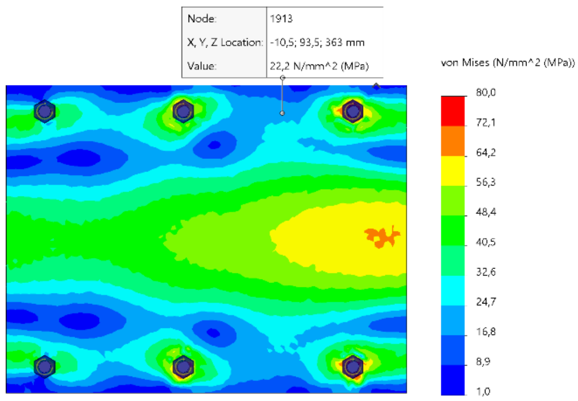


Figure 8: Stress contour plot from FEA

### *4.3. Comparison of experimental and numerical results*

The achieved von Mises stresses are compared as a result. The maximum recorded von Mises stress in Exp. 2 was 21.85 MPa compared to the FEA simulation with 22.2 MPa, which is a difference of 4.9%. See Fig. 9 for a graphical representation of the comparison of achieved stresses, and Fig. 10 for a highlighted area of interest in stress comparison.

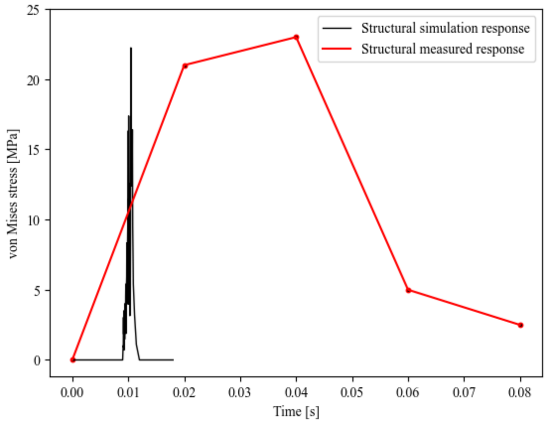


Figure 9: Numerical response compared to experimental for Exp. 2

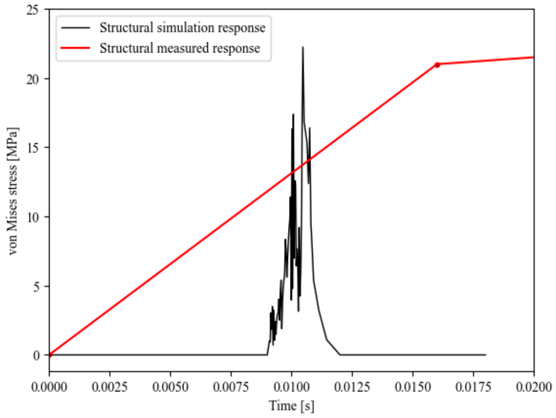


Figure 10: Highlighted area of interest in stress comparison of Fig. 9.

**5. Discussion**

The purpose of this paper was to investigate and compare von Mises stresses from experiments and FEA using SOLIDWORKS Simulation. For the experiments, biaxial strain gauges connected to an HBM DAQ recorded at least two data points at the polycarbonate sheet's stress peak. The numerical simulation was based on the decoupling method. However, instead of using a standard triangular shape for the loading curve, a four-pointed curve (Fig. 5) was used in the simulation. The simulation was run as a non-linear dynamic study. The comparison of the experimental and numerical results shows similarities, as both reached a von Mises stress peak at 22 MPa (± 0.2 MPa).

Since the simulation was based on the recorded internal pressures from the experiments, so was the scaling of time. This resulted in a time scale from 0 sec. to 0.012 sec., set against the strain gauge measurements which scaled from 0 sec. to 0.08 sec. In the simulation result in Fig. 7, the stresses on the polycarbonate reached a maximum stress peak at 0.0107 seconds, with a decreasing value after the peak, ending at 0.012 sec. (also the time the simulation ended). The stresses from the strain gauge measurements did not start to decrease until 0.04 sec for 3 of the 4 experiments. This could possibly be due to the structure's inertia [7] or the DAQ not being able to record smaller stress alternations. During the experiments, a build-up of the loading explosion pressure occurred over a rapid time interval. However, in the simulation, the maximum peak pressure of 1.2 MPa was applied to the structure over a slower time interval of the simulation study. This suggests the possibility for a difference in the stress alternations.

The sampling rate of the DAQ used for strain gauge measurements was low, running at 4.8 kHz versus the pressure transducers running at 100 kHz. This could result in the DAQ being uncapable of recording stresses that could potentially be higher than 21.85 MPa, or stresses occurring between the 0.02 sec. sample intervals. In Fig. 9/10, it is shown that the simulated stresses achieve close to 22 MPa almost immediately, unlike the measured stresses from Exp. 2 which does not achieve any stress peaks prior to 0.02 sec. However, none of the experiments reached a higher total von Mises stress than 21.85 MPa (Exp. 2), while the experiments also were consistent in the measured stresses. The possibility for stress peaks reaching higher than 21.85 MPa between the 0.02 sec. intervals for a total of 4 experiments therefore seems low, meaning that the maximum stress measurements appear to be reasonable.

Limitations of the measuring equipment do clearly give an inaccuracy of the time scaling for comparison of the results. Nevertheless, as this paper focused on analyzing the maximum occurring stresses in the polycarbonate sheet sidewall, the time scale correctness is not especially relevant for this study. In further work, a higher sampler rate DAQ should be used for the possibility of having an exact time scale and to reduce the potential for measurement uncertainty.

**6. Conclusion**

This study demonstrates the use of FEA with SOLIDWORKS for a decoupled numerical simulation, and how the results compare to physical experiments using strain gauges to obtain von Mises stresses. The results show a difference of 4.9% of the maximum achieved stresses. This information and procedure can be helpful for design engineers constructing structures for withstanding explosive or other rapid dynamic loads.

**CRediT authorship contribution statement**

**Daniel Eckhoff:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing.

**Magne Bratland:** Conceptualization, Writing - Review & Editing, Supervision.

**Mads Mowinckel:** Conceptualization, Methodology

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