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COUPLED SIMULATIONS OF EXTREME FLUID-STRUCTURE DYNAMICS

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Abstract. This work presents ongoing research on the influence of fluid-structure interaction (FSI) effects on the ductile crack growth in blast-loaded steel plates. Thin steel plates with X-shaped, pre-formed defects are used to allow for large, inelastic strains and ductile fracture. FSI effects were studied by comparing the numerical predictions of the uncoupled and the coupled FSI approach, where experimental data served as a backdrop to evaluate the accuracy of the numerical simulations. Numerical simulations are conducted in the EUROPLEXUS software. The clear conclusion from this study is that ductile fracture and crack propagation are influenced by FSI effects during the dynamic response of the plate. That is, the crack growth was very sensitive to the actual loading on the plate. Moreover, because the increase in CPU cost may be significant when uniformly refining the mesh, adaptive mesh refinement (AMR) was found very promising in reducing the CPU cost and maintaining the solution's accuracy. The performance of AMR is an interesting finding in the view of numerical simulations of coarsely meshed (prior to AMR) shell structures exposed to blast loading.

1 INTRODUCTION

Fluid-structure interaction (FSI) simulations can be challenging for a number of reasons and are therefore often dependent on the application. One of these challenging applications is the simulation of blast-loading effects on flexible structures undergoing large deformations, possibly up to complete failure. Such simulations require robust and specific FSI algorithms. Recent advancements have managed to establish experimental [1, 2] and numerical [3, 4, 5] frameworks allowing for detailed studies on the FSI during the dynamic response of blast-loaded steel plates. Therefore, a combination of experiments and numerical simulations can be used to obtain better insight into the underlying physics during extreme blast-structure interaction.

It was shown in Ref. [5] that the fluid-structure dynamics introduce a non-uniform spatial and temporal distribution of the loading on the plate. The induced velocity in the plate tends to reduce the pressure during the first part of the FSI phase, while an increase in pressure magnitudes due to the deformed shape of the plate was observed during the second part of the FSI phase.

Although Ref. [6] provides some guidelines on the effect of one single perforation on the yield line locations in two-way supported plates, it is clearly stated that it is difficult to provide detailed guidance on the response of perforated plates. The effect of perforations on the dynamic response of blast-loaded plates is generally a function of location, size and shape.

To date, there are no experimental techniques capable of measuring full-field surface pressures acting on thin plates undergoing large deformations [7]. We are therefore limited to experimental observations of the plate response based on optical imaging and pressure measurements at specific locations in the experimental set-up.

Numerical simulations can be used to investigate the effect of FSI on the dynamic response of plated structures. However, before such methods can be used, it is essential to evaluate their performance in terms of robustness, reliability and effectiveness in predicting both the loading and the dynamic response. Experimental validation is often preferred as it represents the actual physics in the problem, and controlled experiments in laboratory environments can be used to evaluate current computational methods. Previous work [8, 9] studied the influence of FSI effects on the ductile fracture of blast-loaded steel plates with pre-formed square holes. The clear conclusion from this study was that ductile fracture and crack propagation are influenced by FSI effects during the dynamic response of the plate.

This motivates further studies on FSI effects during the dynamic response of steel plates with other types of perforation. This work presents an experimental and numerical investigation of the influence of FSI on the ductile crack growth in a thin, perforated steel plate with pre-formed X-shaped cracks. The use of thin steel plates allows for large, inelastic strains and ductile fracture. Experimental results are already presented by Elveli et al. [2]. However, this study aims for numerical simulations to provide more insight into the influence of FSI effects on crack propagation.

2 SHOCK TUBE TESTS

The blast test was carried out in the SIMLab Shock Tube Facility (SSTF) at NTNU, which has proven to generate controlled and repeatable blast-like loading conditions (see e.g. Ref. [10]). An illustration of the experimental setup, the clamping assembly and a picture of the test specimen are shown in Fig. 1. The experimental results presented in this study were already published in the work in Ref. [2], and the following presentation is therefore limited to a brief overview of the experimental setup.

The plate was manufactured from a sheet of Docol 600DL, had an exposed area of 300 mm × 300 mm, and the blast intensity was chosen such that the plate experienced large deformations (including ductile fracture). Geometrical defects were introduced in the plate prior to testing using wire erosion, initiating ductile fracture and crack propagation in the plate during testing. The defects were represented by four slits rotated 45° with respect to the horizontal and vertical orientation of the plate. The X-shaped defects were positioned symmetrically around the plate centre (Fig. 1b-c). The blast intensity was produced by a nominal firing pressure of 2.5 MPa in the driver and produced a peak reflected pressure of 0.8 MPa ($p_{\mathrm{r,max}}$) followed by an exponential decay over a period of 68.7 ms ($t_{\mathrm{d+}}$). Two high-speed cameras (Phantom v2511) were positioned in a stereoscopic setup and used to capture the dynamic response of the plate, operating at a sampling rate of 37 kHz (Fig. 1a). In addition to the blast test, uniaxial tensile tests were performed to determine the material behaviour (see Ref. [9]).

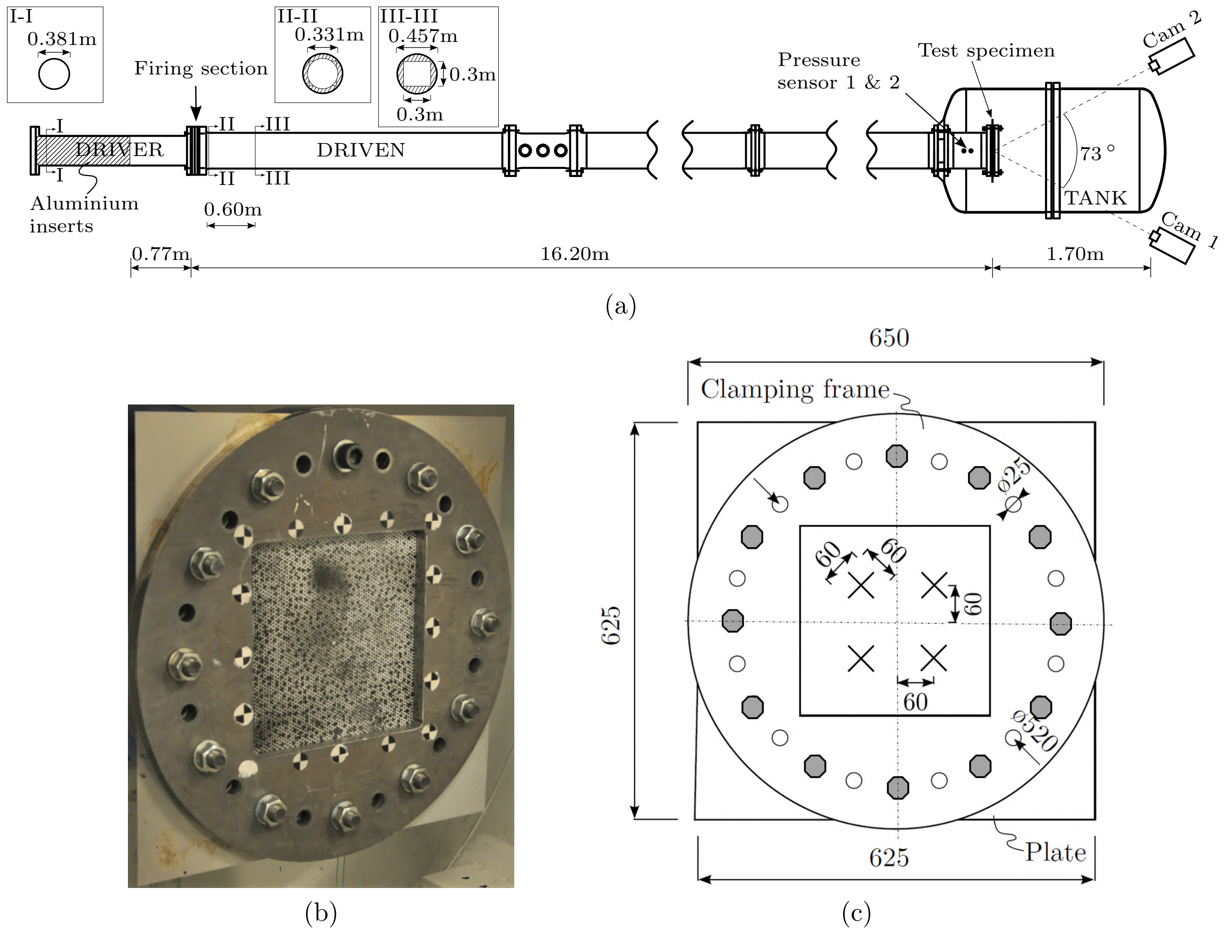


Figure 1: Experimental setup of the SIMLab Shock Tube Facility (SSTF): (a) Sketch of the experimental setup (seen from above), (b) picture of the clamping and DIC speckle pattern for the flexible steel plate (seen from the cameras) and (c) dimensions (in mm) of the clamping assembly. (a) is a reprint from Aune et al. [5].

3 COMPUTATIONAL METHODOLOGY TO STUDY FSI EFFECTS

The numerical simulations were performed by the explicit FE code EUROPLEXUS (EPX) [11]. FSI effects were studied using the numerical methodology presented in Ref. [5], while the high-speed images from the experiment were used as a backdrop to evaluate the predictive capabilities of the numerical models in capturing the actual physics of the problem.

Fig. 2 depicts the assembly of the numerical model, while Fig. 3 from Ref. [5] summarizes the computational strategy. The symmetry planes in the experimental setup allowed to use one quarter (1/4) of the complete assembly shown in Fig. 1.

The fluid sub-domain was discretized with cell-centred finite volumes (CCFV), whereas the clamping assembly and the plate were discretized with solid elements (bricks CUB8 and wedges PR6) and 6 mm Reissner-Mindlin shell elements (quadrangles Q4GS and triangles T3GS), respectively. Contact between the clamping assembly and the plate was modelled using a pinball contact model (see Ref. [9]). Coupling between the structural sub-domain and the fluid sub-domain was achieved by an FSI algorithm of the embedded (or immersed) type, known as *FLSW* in EPX (see Ref. [3] and Fig. 4). This particular algorithm is chosen among the

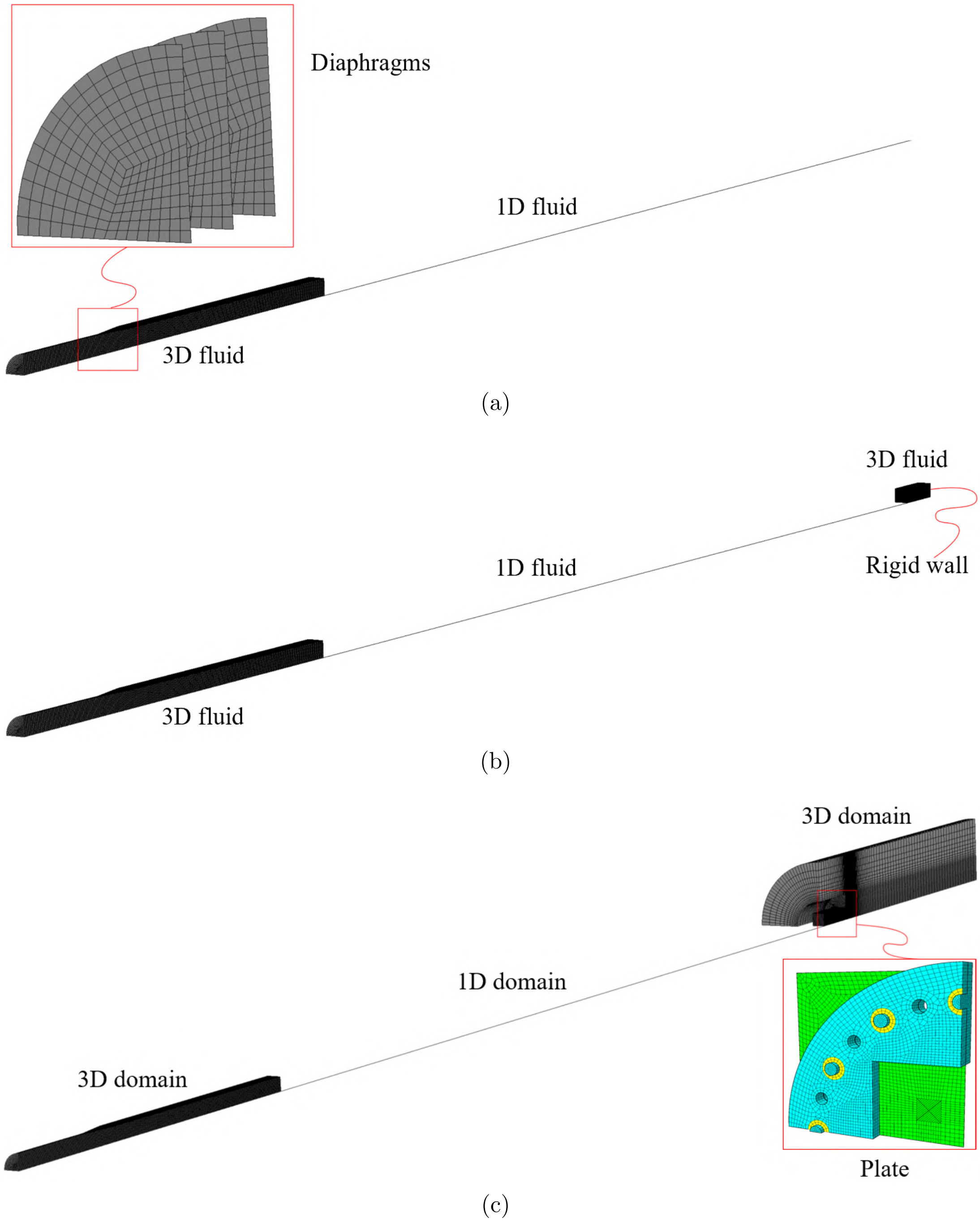


Figure 2: Numerical model (1/4) of the (a) mapping simulation, (b) fluid sub-domain in the first part of the uncoupled approach, and (c) fully coupled FSI approach. The plate assembly shown in (c) was also used (stand-alone) in the second part of the uncoupled approach. (a) and (b) are reprints from Ref. [5].

various others present in EPX for two main reasons. The first reason is the use of CCFV in the fluid sub-domain and the second one is the possibility for the test specimen to undergo large rotations and large deformation, until and even beyond complete failure.

The structure and the fluid are meshed independently and then the structural mesh is sim-

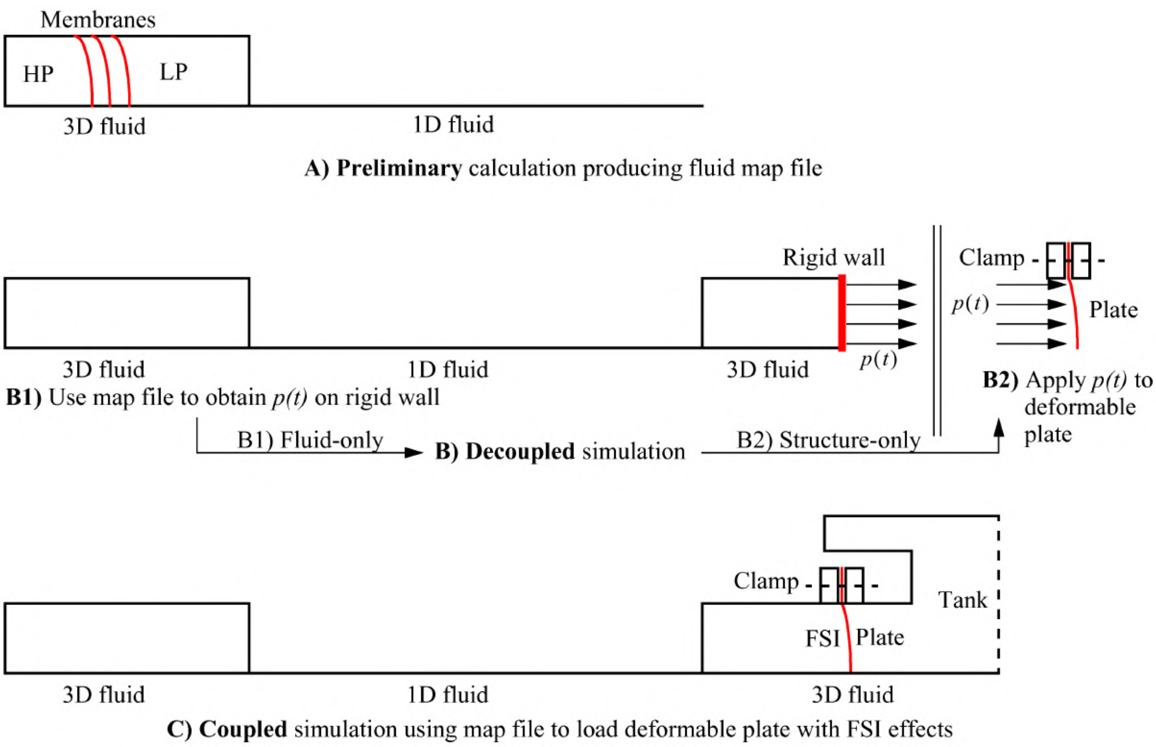
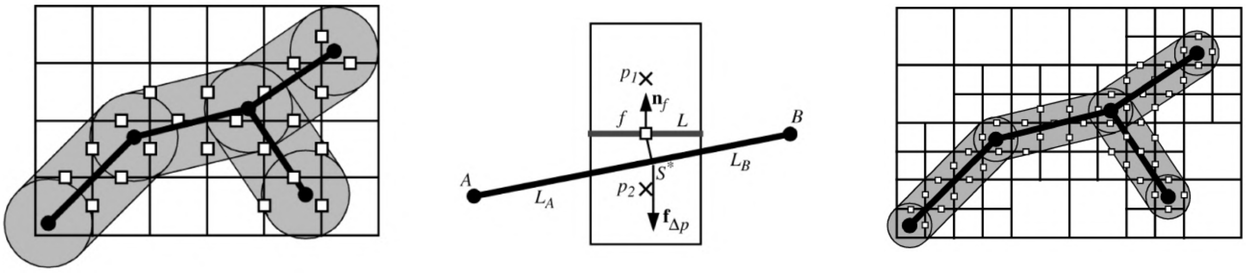


Figure 3: Schematic representation (models not in scale) of the computational strategy (from Ref. [5]). A) Preliminary simulation including detailed modelling of the firing mechanism (membranes) and producing a map file of the fluid conditions right before the shock wave reaches the right end of the 1D fluid sub-domain. B) Decoupled simulation consisting of two parts. First (B1), an Eulerian (fluid-only) simulation using the map file solution as initial conditions in the fluid and producing the pressure time function $p(t)$ on an ideal rigid plate (rigid wall). Second (B2), a Lagrangian (structure-only) simulation including the deformable test plate and the clamping system, using the previously obtained $p(t)$ as loading pressure. C) Fully coupled FSI simulation, using the map file solution as initial conditions in the fluid and including also the embedded deformable test plate and clamping system, allowing to evaluate FSI effects.

ply embedded into (i.e., superposed to) the fluid mesh as shown in Fig. 4a. This simplifies preparation of the numerical model compared with other (mesh-conforming) FSI techniques, but it requires more CPU-intensive calculations and may slightly reduce the accuracy of results for a given size of the mesh. However, this technique is most favourable in the case of large deformations of the structure, see e.g. Ref. [3].

The *FLSW* technique follows a so-called weak coupling based on direct application of fluid forces to the structure. The fluid forces arise from the fluid pressure computed at the CCFV centroids. *FLSW* is the most natural choice when using the embedded approach and CCFVs for the fluid sub-domain [3]. This is opposed to the so-called strong coupling of other FSI techniques based upon constraints (via Lagrange multipliers) on the velocities at the fluid nodes, which is the preferred approach when a finite element discretization is used for the fluid. *FLSW* operates on the numerical fluxes of mass and energy at CCFV interfaces interacting with the structure. These fluxes are blocked (Figure 4b) in order to prevent spurious passage (leakage)



(a) (b) (c)

Figure 4: Weak coupling using CCFVs in the embedded FSI approach: (a) faces in the influence domain, (b) calculation of the pressure drop force $\mathbf{f}_{\Delta p} = (p_1 - p_2)L\mathbf{n}_f$ and (c) improving algorithm spatial resolution by FSI-driven AMR in the fluid (only one refinement level shown for simplicity). (a) and (b) are reprints from Casadei et al. [3], and (c) is reprint from [5].

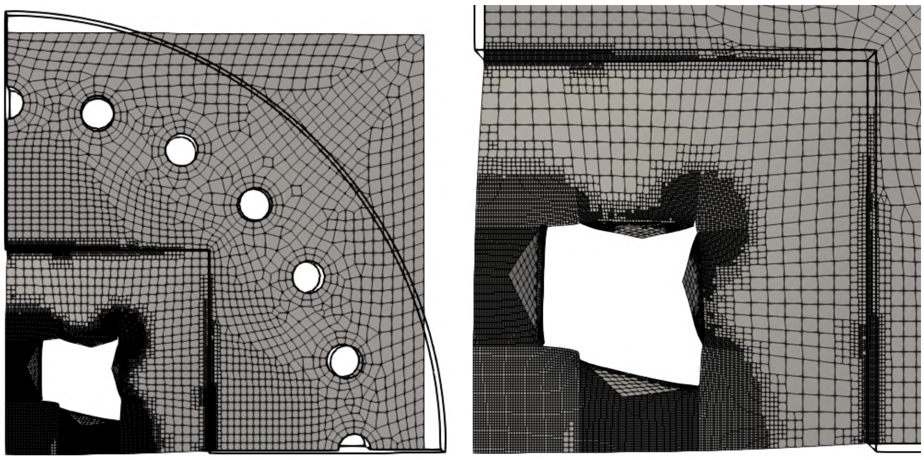
of fluid across the structure, as long as the plate does not fail. This produces a sort of (weak) feedback on the fluid flow, due to the presence of the structure. The fluid forces are assembled with other external forces and subsequently used to calculate the dynamic equilibrium of the structure.

With reference to Fig. 4, in order to determine the portions of fluid (thin regular mesh) interacting with the structure (thick solid lines), the so-called structural influence domain is considered (grey zone). Each CCFV interface (small hollow square) located inside the influence domain transmits a load to the nearest point of the structure, proportional to the pressure drop between the two fluid cells forming the interface. A crucial part of the algorithm is the fast update of the structural influence domain and the fast search for the interacting fluid entities (CCFV interfaces in this case) at each time step of the numerical simulation.

Recent advancements [9, 12, 13, 14, 15] in EPX allow for automatic adaptive mesh refinement (AMR) near the fluid-structure interface (FSI-driven adaptation of fluid mesh), which improves the accuracy of the embedded approach. As shown in Fig. 4c (with just one level of adaptive refinement for simplicity), by reducing the size of the fluid cells close to the structure, the thickness of the structural influence domain can be reduced accordingly, thus increasing the accuracy of the embedded FSI algorithm. FSI-driven AMR was therefore used to refine the fluid mesh at the fluid-structure interface (see Ref. [5]).

The material behaviour was modelled using a modified Johnson-Cook constitutive model (called *VPJC* in EPX) and ductile fracture was included using the Cockcroft-Latham (CL) fracture criterion [16]. Material parameters for the steel under consideration were taken from Ref. [9]. Damage-based AMR was activated in the plate using a threshold criterion ($0.01 \leq$ D ≤ 0.02) on the CL fracture parameter, allowing for element erosion without too much loss of mass. Fig. 5 shows the mesh at 1.50 ms after the time of impact in the FSI simulation, showing both the entire (1/4) numerical model (Fig. 5a) and a closer view of the AMR in the blast-exposed area of the plate (Fig. 5b).

FSI effects were studied by comparing the numerical predictions of an uncoupled and a coupled FSI approach. The uncoupled approach (**B2** in Fig. 3) contains only the clamping assembly and the plate, where a time-dependent but spatially uniform pressure is imposed on the blast-exposed area of the plate. The pressure history was obtained in a separate simulation (**B1** in Fig. 3) containing only the fluid sub-domain where the plate is assumed to be a rigid wall.



(a) (b)

Figure 5: Illustration of the damage-driven AMR in the FSI simulation at 1.50 ms after the time of impact: (a) the mesh of both the plate and the clamping assembly and (b) a closer view of the AMR in the blast-exposed area of the plate.

Thus, the uncoupled simulations make the inherent assumption that the pressure is unaltered by the structural motion, and vice versa. The uncoupled approach is therefore a conservative simplification of the real behaviour because it is expected to overestimate the actual pressure on the plate (see e.g. Ref. [5]).

Finally, a simulation following the coupled approach (**C** in Fig. 3) was carried out including the entire model, i.e., both the fluid and structural sub-domain in the same simulation. This allowed for numerical investigations on FSI effects during the dynamic response of the plate, by comparisons to the numerical results obtained with the uncoupled approach.

It is important to emphasize that both the Eulerian simulation in the uncoupled approach (**B1** in Fig. 3) and the FSI simulation in the coupled approach (**C** in Fig. 3) started from the same initial conditions in the fluid sub-domain (map file, **A** in Fig. 3), ensuring that the incoming blast wave is identical in both approaches. This allows for numerical investigations on FSI effects during the dynamic response of the plate.

4 RESULTS

Fig. 6 shows a comparison of crack initiation and crack propagation during the experiment, the uncoupled simulation, and the coupled simulation. The comparisons are shown at characteristic times representing the overall trends in this study. Mirroring across the symmetry planes are used to illustrate the complete (4/4) model for the plate in the simulations.

The effects of the pre-formed defects on the dynamic response of the plate are as expected and according to the guidance given in Ref. [6] and previous observations in Ref. [8]. That is, the cracks initiate at the extremities of the defects and the defects therefore define the crack paths. It is found that both the uncoupled and the coupled approach predict crack initiation and crack propagation in the plate. In fact, it is evident that the coupled approach (see Figs. 6g-i) is very close to the experimental observations (see Figs. 6a-c). The coupled approach succeeds in predicting the arrested cracks (see Figs. 6i), whereas the uncoupled approach results in a complete fracture of the plate (see Figs. 6f). This is more or less as expected and according to

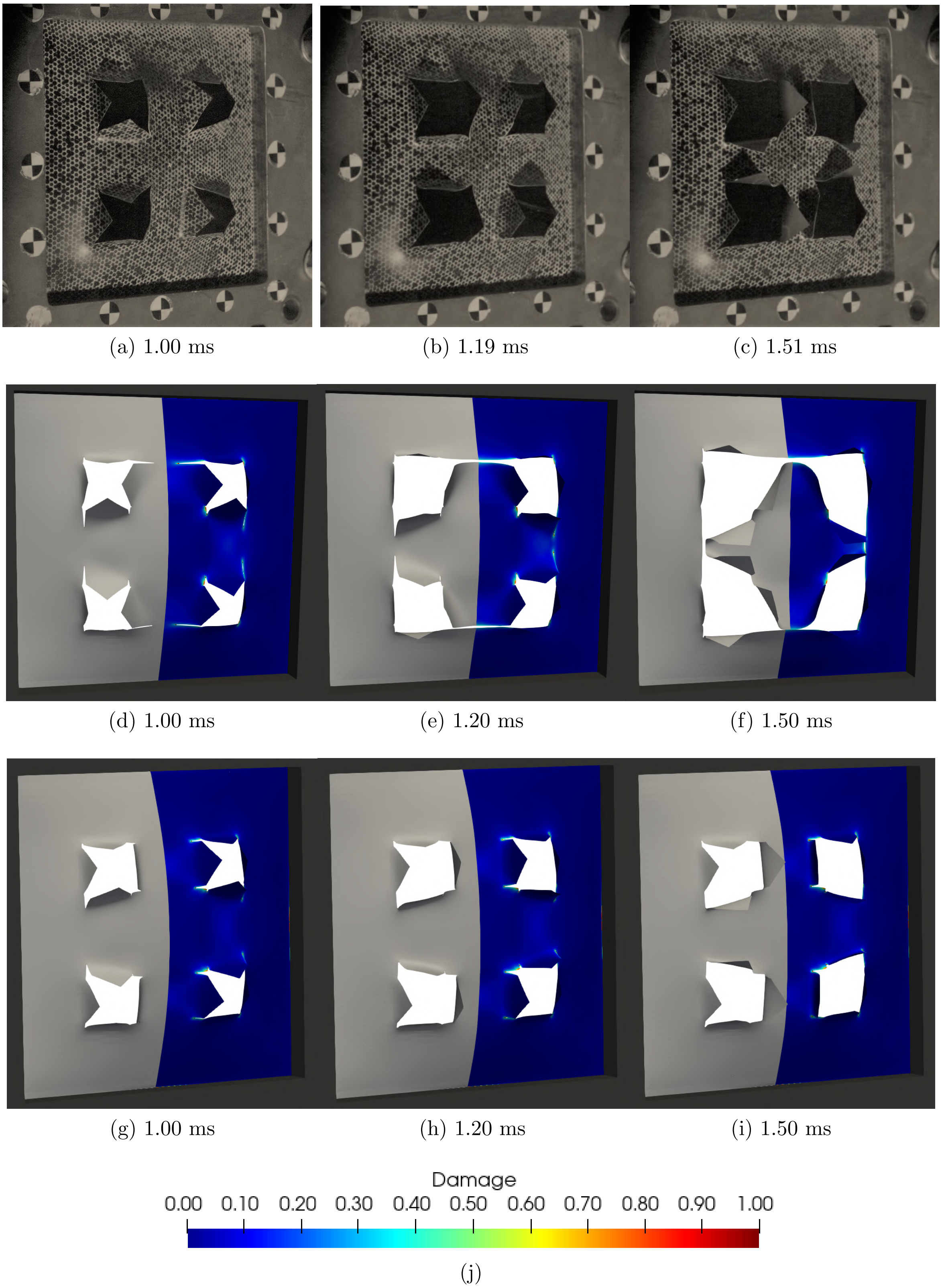


Figure 6: Comparison between the experimental observations (top row) and the damage evolution in the uncoupled simulation (middle row) and coupled simulation (bottom row). Fringe colours represent the normalized damage in the plate. Time zero (t = 0) is taken as the time of impact of the shock wave on the test specimen.

previous studies on the influence of FSI effects of thin steel plates (see e.g. Refs. [5, 8]). That is, the uncoupled approach is conservative in the way that the crack propagation is faster in the uncoupled simulation compared to the experimental observations (see Figs. 6a-c and 6d-f).

It was interesting to note that the cracks did not propagate along the diagonals (i.e., the yield lines) as the crack paths in the uncoupled approach form along the vertical and horizontal lines in-between the pre-formed defects (see Figs. 6d-e). It is important to keep in mind that the coupled simulation includes significant complexity compared to the uncoupled approach, and that the crack propagation is very sensitive to the magnitude of the loading. The results from this study could be used to conclude that there is a noticeable influence of FSI on crack growth in the plate. However, the results should be used with caution and detailed investigations on the performance of the coupled FSI model should be carried out to evaluate its reliability in predicting the actual loading during the experiments. Such investigations are beyond the scope of this study and are suggested as further work.

Fig. 7 shows a comparison of the pressure distribution on the plate for the uncoupled and the coupled FSI approach at the same characteristic times as in Fig. 6. Note that in the uncoupled approach a uniform (but time-dependent) pressure is applied to the entire plate area exposed to the blast. In fact, this pressure results from a purely fluid simulation assuming a rigid wall at the end of the shock tube, see Fig. 2b. Experimental pressure fields are not included because it is not possible to obtain these from the experimental data. To date, there is no measurement technique allowing us to determine the full-field surface pressures during the dynamic response of flexible plates experiencing large deformations (see e.g. Ref. [7]). The investigation of the surface pressures acting on the plate is therefore based only on the numerical results.

As expected, the pressure distribution is significantly influenced by the dynamic response of the plate. It is also observed a reduced pressure magnitude in the coupled approach (Figs. 7d-f) compared to that in the uncoupled approach (Figs. 7a-c) similar to that in Refs. [5, 8], where the pressure at the plate centre and in-between the outer extremities are higher than in the remaining parts of the plate (Fig. 7d). Then, as the petals surrounding the pre-formed slits start to rotate and deform, the coupled approach clearly indicates a reduced pressure acting on the petals during the deformation process. Hence, the effect of reduced pressure loading was most evident in the vicinity of the pre-formed slits and for the petals closest to the plate centre (see blue fringe colors in Fig. 7f).

It is important to emphasize that the inherent assumption of the uncoupled approach implies that the loading is unaltered by the deformation of the plate and that the pressure is always acting perpendicularly to the front surface of the plate. This implies that the pressure is overestimated as the plate fails because the pressure will be vented into the tank (see Fig. 1). That is, the fracture mode is non-physical as the plate undergoes excessive, large displacements in the uncoupled simulation (Figs. 6d-f and 7a-c). If the plate is sufficiently deformed, one may end up in a situation where the load applied on the petals is acting in the opposite direction to the initial blast load (Fig. 6e-f). It is therefore expected that the coupled approach is closer to predicting the actual loading on the plate. Future studies will therefore focus on a broader scope of defect geometries and plate materials to further assess the performance of the uncoupled and coupled simulations.

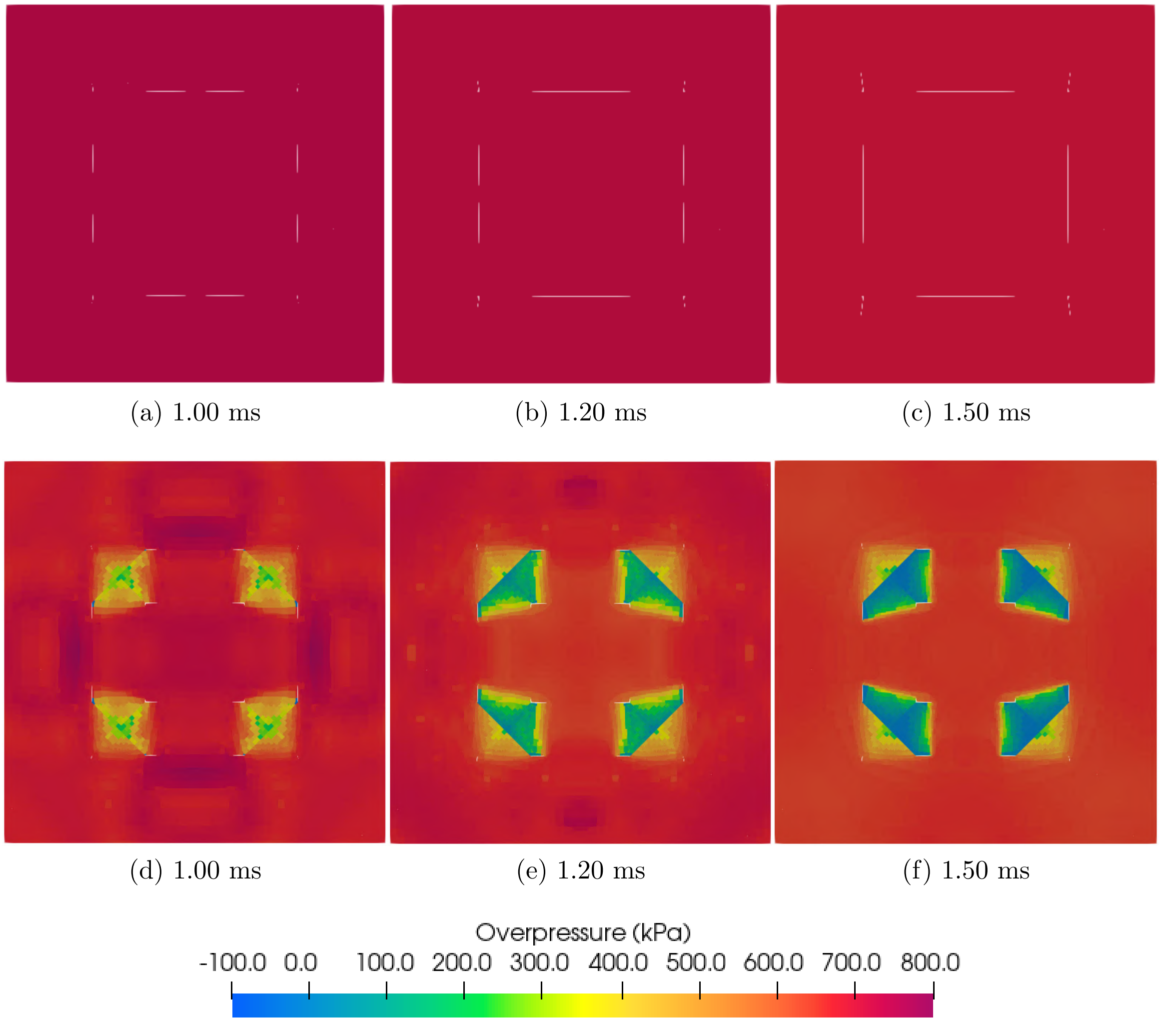


Figure 7: Comparison of the pressure distribution on the plates for the uncoupled (top row) and the coupled (bottom row) approach at the same characteristic times as in Fig. 6. Fringe colours represent the contour map of the overpressure (in kPa) acting on the plate. The pressure fields are obtained using the *EFSI* directive in EPX and mapped to the initial configuration of the nodes to better visualize the pressures during large deformations of the plate.

5 CONCLUDING REMARKS

This study investigates the influence of FSI effects on the dynamic fracture of blast-loaded steel plates with X-shaped pre-formed defects. Such effects were studied by comparing the numerical predictions of the uncoupled and the coupled FSI approach. Special focus was placed on the influence of FSI on the ductile crack growth in the plates, where experimental data served as a backdrop to evaluate the accuracy of the numerical simulations. The main conclusions from the study are as follows.

- The clear conclusion from this study is that the ductile fracture and crack propagation are influenced by FSI effects during the dynamic response of the plate. That is, the crack growth was very sensitive to the actual loading on the plate.

- FSI effects were observed on the ductile crack growth and as non-uniform spatio-temporal pressure distributions on the blast-exposed area of the plate.
- Although crack initiation was similar in both the uncoupled and coupled simulations, crack propagation showed some distinct differences. The coupled approach experienced crack arrest and was therefore very close to the experimental observations, whereas the uncoupled approach was conservative in that the crack propagation was faster compared to the experimental observations.
- The inherent assumption of the uncoupled approach fails to predict the experimentally observed crack propagation. This resulted in overly conservative predictions of the crack propagation and inaccurate fracture patterns in the plate. The coupled (FSI) simulations indicate a reduced pressure acting on the petals during the deformation process. The effect of reduced pressure loading was most evident in the vicinity of the pre-formed slits during the deformation of the plate.
- It is emphasized that this work is ongoing research and that the presented results should be used with caution. More detailed studies on the reliability of the coupled FSI simulations are planned as further work. Still, the computational methodology used in this study has proven to be well suited to study the influence of FSI on the ductile crack growth in blast-loaded steel plates. This motivates similar studies on even more complex geometries.

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