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AN APPROACH FOR A NOVEL MULTISCALE PARTITIONED FRAMEWORK FOR PREDICTING COLLAPSE OF BUILDINGS UNDER FIRE LOADS

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Abstract. The structural integrity and load-bearing capacity of burning buildings can be significantly reduced due to high thermal load. This causes a problem for e. g. rescue workers, as they have to ensure the rescue of people in a burning building even if there is an increased risk of collapse. Predicting safe routes in and out of a burning building is a difficult task that takes resources and expertise. Alternatively, escape routes can be identified using simulations, which require a multidisciplinary and multiscale approach. These simulations may either run in real-time or need to be coupled with artificial neural networks in order to train them such that these neural networks suggest safe escape routes in real-time in case of a fire incident. Computational-fluid-dynamic simulations of the fire provide information about both the temperature and the smoke distribution in the single rooms of a building. Micro-scale simulations describe local material behaviour such as spalling and cracks. Structural-scale analysis provides information about the global structural behaviour of the building including a possible progressive collapse. Nevertheless, a coupling of these multi-physical simulations is needed to identify safe escape routes in a burning building. However, it is not only necessary to couple across scales but also across software platforms, as there is – to the best knowledge of the authors – no simulation framework available that can calculate the stated effects on multiple scales with good accuracy. Consequently, studying these fire-structure interactions necessitates an accurate computational simulation framework that integrates the effects of different physical phenomena. The objective of this contribution is to provide a computational framework for fire-structure simulations to elucidate the interplay between damage of concrete and progressive collapse. In the proposed computational setup, two software packages are used to simulate material damage and the resulting collapse of an exemplary structure under fire. A micro-scale model uses a FEniCs-based solver for the concrete material and a structural-scale model uses ABAQUS for the (progressive) collapse simulation. These solvers exchange information on temperature, stress, and changes in geometry across scales and software through an open-source coupling library, preCICE. The proposed model is illustrated by a numerical experiment that forecasts the damage leading to progressive collapse.

1 INTRODUCTION

In Europe, fires in large buildings claim the lives of almost 5,000 people every year [1]. From 2014 to 2018, the average annual property damage in the United States was above 10 billion USD, according to the National Fire Protection Association (NFPA) [2]. If a high-storey building structure is on fire, the structural elements that are (locally) exposed to fire are subjected to a tremendous amount of heat load. Dead- and payload and the additional thermal load may cause the structure to deteriorate and eventually cause the building to collapse. Therefore, this brings the necessity to both (i) understanding the material behaviour of concrete under fire and to combine this with (ii) the simulation of progressive collapse of the building under fire load.

Multi-scale simulations considering different physical phenomena such as e. g. fire dynamics, concrete behaviour under fire, local damage, global effects due to damage, redistribution of the loads and displacements, and structural dynamics are computationally expensive. Also, to create such a computational framework is challenging and cumbersome. Fire-structure interaction simulations have been investigated for quite some years. Coupled simulations using hybrid methods for fire-structure interactions are attempted in [3, 4]. Herein, fire was simulated from the fire dynamic simulator and the temperature distribution was given as an input to the structural solver leading to a combined fire-structure simulation. However, these examples were limited to small-scale problems limited to the size of e. g. a wall. In [5] a possible framework for fire-structure simulation using artificial neural networks including progressive collapse is described. An enhanced fire-structure simulation on a sub-structural level combining the ISO-fire curve and a user-defined material model is shown in [6]. A hybrid approach using experimental data on the sub-structural scale to provide information about the state of structural members at the building scale is given in [7].

In order to simulate the damage, in recent times the phase field method has been used. It models crack initiation, propagation, branching and merging in an effective manner by employing the continuum phase field fracture approach [8]. Phase field method is widely used to simulate brittle fracture [9], fracture due to coupled multi-physics processes [10, 11], and was recently extended to an alternative based on shape optimization [12]. To simulate damage in concrete the classical phase field method was extended to incorporate cohesive effects as a unified phase field approach in [13]. Due to the effectiveness and ease of implementation, the phase field method is used in this work to simulate the local concrete damage under fire.

In this paper, a novel computational framework is proposed, an extension of the authors' previous works [5,14], where two different simulation instances (solvers) are used to simulate the progressive collapse at the structural scale and fully coupled thermo-mechanical fracture due to fire at the sub-structural scale. This strategy allows to solve different physical phenomena in different scales and software packages and combine the individual advantages of each solver. Thus saving computational time and reducing the complexity of incorporating all mechanisms into the same software. This allows for reliable forecasts regarding the progressive damage.

The outline of this contribution is as follows: section 2 specifies the coupling framework and the details regarding the implementation and functions of the coupling. Details about the simulations at the structural scale and the sub-structural scale are described briefly in the following sections 3 and 4, respectively. Next, in section 5 the boundary value problem mimicking the simplified fire-structure interaction is defined and results of the conducted numerical experiments regarding the progressive collapse of the structure under fire are shown in section 6. Finally, the findings are summarised in section 7.

2 COUPLING FRAMEWORK

In a progressive collapse of buildings under fire, multi-scale simulations with local temperature effects and global structural effects can be computationally expensive in any simulation software. According to the authors' knowledge, there exists no open-source or commercial software that can simulate reliably such a multi-scale fire-structure interaction. For such a fire-structure simulation, the following challenges need to be taken care of: simulation of different partial differential equations (PDEs) on both scales, different FEM meshes on both scales, two-way data transfer, time-stepping schemes given that different PDEs are solved on both scales, etc. In addition, it will be challenging to further enhance the simulation framework in order to include additional extensions or advancements in treated mechanisms on both scales.

Therefore, two different simulation instances (solvers) are created which have unique simulation settings such as specific mesh and time steps. Both simulation instances (solvers) are coupled using the external coupling library `preCICE` [15]. It connects both solvers, which each simulate one part of the complete physics involved in this simulation. It is an open-source partitioned multi-physics coupling library that is responsible for time step control, data transfers, and data interpolation between both solvers. This coupling methodology using `preCICE` makes it simple to develop both simulation instances separately and assess the combined effects of both solvers while maintaining the lower computational costs.

In this work, the progressive collapse of a structure under fire is simulated in two distinct solvers, which are the structural scale solver using ABAQUS and the sub-structural scale solver using `FEniCs`. The coupling framework is visualised in figure 1. Each solver simulates a part of the problem on respective scales and communicates the data to the other solver at every predefined coupling time step $\mathrm{d}t_{\mathrm{coupling}}$. A serial explicit time marching scheme is used from `preCICE` to exchange the data between the solvers. For data interpolation between different meshes a nearest-neighbour interpolation scheme is used. In this modelling strategy, structural solver time step $\mathrm{d}t_{\mathrm{struct}}$, sub-structural solver time step $\mathrm{d}t_{\mathrm{sub}}$, and coupling time window $\mathrm{d}t_{\mathrm{coupling}}$ are defined. Respective solver time steps were chosen independently concerning the mesh complexity and acceptable evolutions of the displacements and damage.

3 STRUCTURAL SOLVER

The structural solver is using the commercial FEM software ABAQUS to model the structural scale e. g. building scale and simulating progressive collapse. Based on the dead load and payload, which are not considered in the sub-structural model, the stress and strain distribution in the building are calculated with an implicit dynamic approach by solving the equation of motion.

On the building scale, the model is discretised with 4-node plane strain elements (CPE4), for the concrete, a linear elastic material model is used, which is defined in the ABAQUS subroutine UMAT. The UMAT subroutine not only initialises the communication – using `preCICE` – between the two solvers, but also makes the stress and strain distribution available for use in the sub-structural solver. Therefore the stiffness matrix $\mathbf{C}$ is defined inside UMAT and called at every GAUSS-point and for every time increment $\mathrm{d}t_{\mathrm{struct}}$ to calculate stresses $\boldsymbol{\sigma}$ and strain energy density ψ_{mech}. The stresses, strains and corresponding GAUSS-point coordinates are stored and made accessible for communication with `preCICE`.

The damage caused by the fire combined with the external loads is calculated in the sub-structural model and introduced in the structural model – again using `preCICE` – through a damage variable d. This damage variable d acts as a scaling factor for the stiffness of each element and therefore controls the degree of damage. In detail, $d = 1$ means a fully damaged element and $d = 0$ indicates an undamaged element. If $d = 1$ at a given GAUSS-point, the corresponding element is deactivated or deleted, which means that the stress values become zero

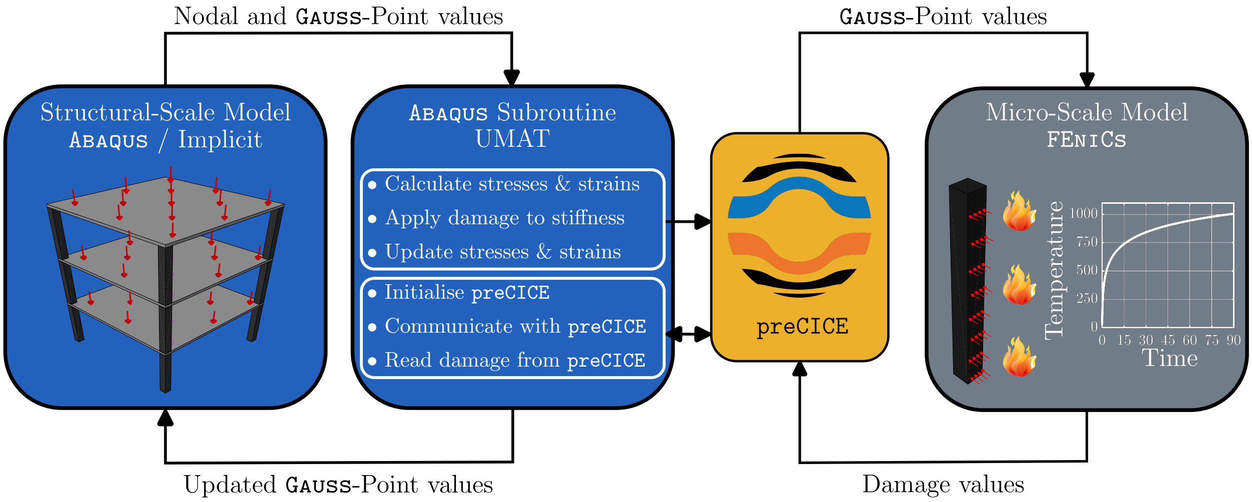

Figure 1: Coupling framework for ABAQUS and FEniCs using preCICE library inspired by [16]

and the failed element can not carry any load anymore. As soon as a certain amount of elements failed in a sub-structural member, e. g. a column, the whole structural member is considered to have failed.

A fully damaged structural member initiates a subsequent simulation addressing the progressive collapse.

4 SUB-STRUCTURAL SOLVER

In the sub-structural solver, a fully coupled thermo-mechanical solver is used to compute the damage using the phase field method. In this solver, the following partial differential equations (PDE) are solved in a staggered manner in software FEniCs [17]: thermal PDE, mechanical PDE, and phase field (fracture) PDE. It should be noted that – as a first modelling approach – the sub-structural components are modelled to be made from unreinforced concrete, i. e., reinforcing is not considered at this scale, yet. Once the reinforcing is modelled, too, its actual corrosion state [18] needs to be incorporated in order to be able to deal with different ages of the respective building.

In this sub-structural solver, the model is discretised using triangular elements with 3 nodes in a plane strain setting. An implicit time marching scheme is used for the evolution of the primary variables. Evolutions of the thermal, mechanical, and damage fields are solved in a staggered manner until convergence with a tolerance of $||\boldsymbol{r}|| < \mathrm{tol}_{\mathrm{stag}} = 1 \times 10^{-3}$ is reached. Thereafter, obtained phase field damage values are transferred, to the respective GAUSS-points in structural - solver - mesh, using nearest-neighbour interpolation scheme without any further algebraic changes. This facilitates the weakening of the respective local stiffness at the structural scale which leads reduction in load-carrying capacity.

5 NUMERICAL EXAMPLE

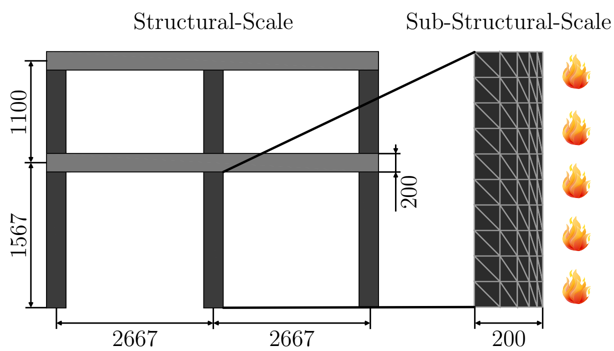

Figure 2: Boundary value problem: (left) building at structural scale; (right) sub-structural column exposed to fire, dimensions in mm

An exemplary two dimensional boundary value problem, based on the investigation in [19], is defined to prove the coupling concept. A one-storey concrete building supported on three columns is considered at the structural scale, and one of the columns is assumed to be exposed to local fire conditions, as shown in figure 2. The dimensions are in millimetres. At the structural scale a linear elastic material model – not considering thermo-physical material properties – is used. Since the fire is modelled locally, the thermo-mechanical response is computed at the sub-structural scale by using thermo-physical material properties of concrete taken from [20]. Evolution laws of the temperature-dependent parameters are taken from DIN standard-1992 [21]. As a first modelling approach, no reinforcing is taken into account in both solvers.

For the sub-structural scale, thermo-mechanical fracture simulation of concrete columns is performed using the phase field method. ISO fire curve from [22] is used for input temperature boundary conditions at the fire-exposed side of the column. Due to the high thermal load, the mesh of the concrete column is refined in the direction of the fire-exposed surface to avoid convergence problems. On the structural scale, a dynamic implicit FEM simulation is used to analyse the stresses in the structure caused by external mechanical loads. The structure is loaded linearly in the first 60 s to 10 $\frac{\mathrm{kN}}{\mathrm{m}}$ distributed load on the beams. The sub-structural scale model introduces damage caused by the fire on the middle column of the fully loaded structure. After the failure of the middle column – as an initiation for the progressive collapse – the stress redistribution on the structural scale is calculated.

Adaptive time stepping is used for both solvers and the `preCICE` coupling. The time step for structural solver in ABAQUS ranges from $\mathrm{d}t_{\text{struct}} = 1 \times 10^{-4}$ s to 9 s. The sub-structural solver time step in `FEniCs` ranges from $\mathrm{d}t_{\text{sub}} = 1 \times 10^{-4}$ s to 2 s. Additionally, the time window of the coupled simulation framework is defined with the first-participant method [15], where ABAQUS decides the coupling time window as $\mathrm{d}t_{\text{coupling}} = \mathrm{d}t_{\text{struct}}$.

6 RESULTS

In this section, the results of the redistribution of the reaction force and the damage evolution are discussed.

Figure 3 depicts the normalised reaction force in y-direction for the total simulation time of 800 s. The dead load is applied in the first 60 s and remains constant until the end of the simulation. Analogously, the reaction force increases in the columns.

Due to the effects of the thermo-mechanical damage to the middle column and the resulting reduced ability to carry loads, the reaction forces in all columns are redistributed. As expected, more and more loads have to be carried by the outer columns. After 700 s, the middle column fails and can no longer support any load. This is shown in figure 3 by the drop of the reaction force, of the middle column, to zero. The load is now completely redistributed to the two neighbouring columns, which is reflected in an abrupt increase in reaction force.

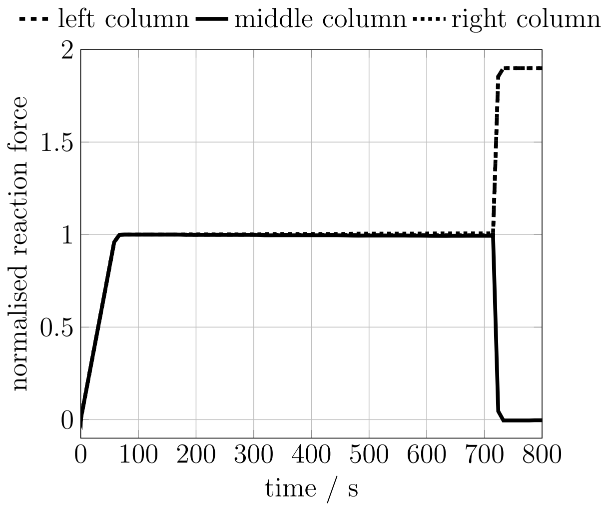

Figure 3: Normalised reaction force over time in y-direction for bottom columns

The damage evolution of the structure can be observed in figure 4. Herein, the evolution of thermo-mechanical damage to the middle column due to fire exposure can be noted for 0 s, 150 s, and 700 s respectively. On the right side of figure 4 the evolution of the phase field value is shown, which is calculated in the FENICS solver. With increasing time, the fire temperature rises and is transferred into the middle column as an input boundary condition.

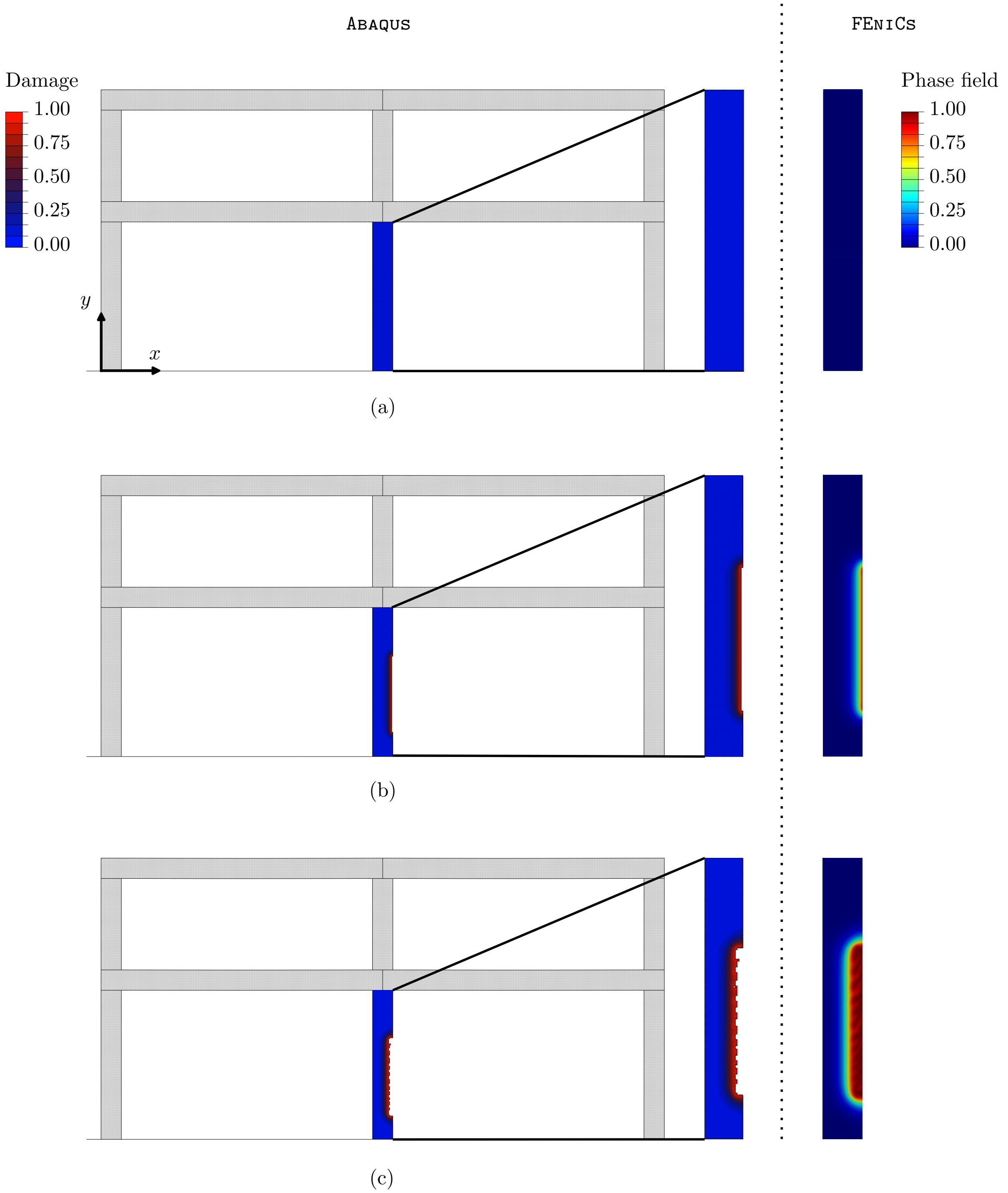

Figure 4: Evolution of the damage over time at (a) 0 s, (b) 150 s and (c) 700 s

On the left side of figure 4 the evolution of the damage in the ABAQUS model is shown. It can be seen, that the damage follows the phase field as a result of the working coupling between the two solvers. The transferred damage value successively scales the stiffness of the elements until $d = 1$ is reached and the respective elements are deleted. This can be seen in figure 4 (b) and (c).

7 CONCLUSIONS

In this contribution, a computational framework for solving multi-scale progressive collapse simulation is suggested. In computational modelling, a fully coupled thermo-mechanical fracture evolution is solved at the sub-structural scale and coupled with a dynamic progressive collapse simulation at the structural scale. This framework lays out the potential for coupling with additional solvers to include further physical phenomena. As a numerical experiment, an exemplary boundary value problem was formulated and investigated to track the global effects on the concrete structure due to local damage resulting from the fire load. The extension of the framework to include different components, such as 3-dimensional columns and walls in both solvers, is planned for future work.

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REFERENCES

[1] Modern Building Alliance. https://www.modernbuildingalliance.eu/EU-fire-safety-guide, 2019.

[2] M. Elshorbagi and M. AlHamaydeh. Simulation of rc beams during fire events using a nonlinear numerical fully coupled thermal-stress analysis. *Fire Numerical Simulation*, 6(57), 2023.

[3] J.A. Feenstra, H. Hofmeyer, R.A.P. Van Herpen, and M. Mahendran. Automated two-way coupling of cfd fire simulations to thermomechanical fe analyses at the overall structural level. *Fire Safety Journal*, 96:165–175, March 2018.

[4] L. Chen, C. Luo, and J. Lua. Fds and abaqus coupling toolkit for fire simulation and thermal and mass flow prediction. *Fire Safety Science*, 10:1465–1477, 2011.

[5] W. Weber, C. Kandekar, M. Rottmann, M. Breuer, A. Palani, O. Niggemann, and A. Liebert. *dtec.bw-Beiträge der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg*, volume 1 of *Forschungsaktivitäten im Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr dtec.bw*, chapter Increasing the safety of rescue workers in fire events by merging fire simulations, structural models, and artificial intelligence, pages 281–286. D. Schulz and A. Fay and W. Matiaske and M. Schulz, 2022.

[6] Mohsen Roosefid, Marie-Hélène Bonhomme, and Pierre Pimienta. Contribution to the modelling of the structural behavior of reinforced concrete walls under iso fire exposure. *Fire Technology*, 59(6):3185–3201, July 2023.

[7] Yu-Shuang Wang, Hao Zhou, and Jian-Ying Wu. Hybrid fire collapse simulation of reinforced concrete structures under localized fires. *Engineering Structures*, 292:116525, October 2023.

[8] Tymofiy Ambati, Marreddy andGerasimov and Laura De Lorenzis. A review on phase-field models of brittle fracture and a new fast hybrid formulation. *Computational Mechanics*, 55(2):383–405, 2015.

[9] Fadi Aldakheel, Nima Noii, Thomas Wick, Olivier Allix, and Peter Wriggers. Multilevel global–local techniques for adaptive ductile phase-field fracture. *Computer Methods in Applied Mechanics and Engineering*, 387:114175, 2021.

[10] Fadi Aldakheel, Chaitanya Kandekar, Boris Bensmann, Hüsnü Dal, and Richard Hanke-Rauschenbach. Electro-chemo-mechanical induced fracture modeling in

proton exchange membrane water electrolysis for sustainable hydrogen production. *Computer Methods in Applied Mechanics and Engineering*, 400:115580, 2022.

[11] Chaitanya Kandekar, Aravinth Ravikumar, Daniel Höche, and Wolfgang E. Weber. Mastering the complex time-scale interaction during stress corrosion cracking phenomena through an advanced coupling scheme. *Computer Methods in Applied Mechanics and Engineering*, 428:117101, 2024.

[12] Tim Suchan, Chaitanya Kandekar, Wolfgang E. Weber, and Kathrin Welker. Crack propagation in anisotropic brittle materials: from a phase-field model to a shape optimization approach. *Engineering Fracture Mechanics*, 303:110065, 2024.

[13] Jian-Ying Wu. A unified phase-field theory for the mechanics of damage and quasi-brittle failure. *Journal of the Mechanics and Physics of Solids*, 103:72–99, 2017.

[14] A. Palani, C. Kandekar, M. Breuer, and W. E. Weber. Toward coupled fire-structure simulations for forecasting smoke leakage in case of concrete structures under fire. *Proceedings in Applied Mathematics and Mechanics*, 23(3):e202300250, 2023.

[15] G. Chourdakis et al. preCICE v2: A sustainable and user-friendly coupling library. *Open Research Europe*, 2:51, 2022.

[16] `www.precice.org`, 2024.

[17] M. S. Alnaes, J. Blechta, J. Hake, A. Johansson, B. Kehlet, A. Logg, C. Richardson, J. Ring, M. E. Rognes, and G. N. Wells. The FEniCS project version 1.5. *Archive of Numerical Software*, 3, 2015.

[18] Mohamadreza Shariati, Wolfgang Weber, and Daniel Höche. Parallel simulation of the poisson–nernst–planck corrosion model with an algebraic flux correction method. *Finite Elements in Analysis and Design*, 206:103734, 2022.

[19] Yi Li, Xinzheng Lu, Hong Guan, and Lieping Ye. An improved tie force method for progressive collapse resistance design of reinforced concrete frame structures. *Engineering Structures*, 33(10):2931–2942, October 2011.

[20] Robert Jansson. *Material properties related to fire spalling of concrete*. PhD thesis, Division of Building Materials, 2008.

[21] Eurocode 2: Design of concrete structures – part 1-2: General rules – structural fire design. Standard, DIN Deutsches Institut für Normung, Berlin, DE, March 2021.

[22] ISO 834-1:1999: Fire-resistance tests — elements of building constructionpart 1: General requirements. Standard, International Organization for Standardization, Geneve, CH, 1999.