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MODELING CONCRETE FLOW IN FORMWORK USING TWO-WAY FLUID-STRUCTURE INTERACTION

Kout K.[1], **Němeček J.**[2], **Němeček J.**[3]

Abstract: *This article investigates the lateral pressure exerted by fresh self-compacting concrete on vertical formwork using an implicit coupled two-way fluid-structure interaction (FSI) approach. Fresh concrete is modeled by the Herschel-Bulkley rheological model, while the formwork is represented as a deformable elastic structure. A three-dimensional numerical model implemented in ANSYS software enabled continuous simulation of the fluid domain due to formwork deformation during casting. The results indicated that the two-way coupling approach provides a more realistic description of concrete-formwork interaction and serves as a reference for assessing the applicability of simplified pressure prediction models. The obtained results confirm that the predicted lateral pressure remained within typical design limits of standard formwork systems, while the corresponding deformation levels were consistent with the assumed support conditions.*

Keywords: Self-compacting Concrete, Volume of Fluid, Computational Fluid Dynamics, Two-way Fluid-structure Interaction, Formwork

1. Introduction

Self-compacting concrete (SCC) has become a standard material in contemporary construction practice, primarily due to its high flowability and ability to completely fill formwork without the need for mechanical compaction Geiker and Jacobsen (2019). Despite these advantages, the lateral pressure acting on vertical formwork during casting represents a major design concern. Because fresh SCC exhibits pronounced fluid-like behavior, the resulting pressures may approach hydrostatic conditions, which can significantly increase the structural demands on formwork systems Gowripalan et al. (2021). Reliable prediction of this pressure is therefore a key requirement for ensuring both structural safety and cost-effective formwork design.

The common practice of formwork designs typically assumes hydrostatic pressure, neglecting the time-dependent rheological behavior of fresh concrete. Experimental studies have shown that thixotropy and structural buildup can significantly reduce the exerted pressure compared to the hydrostatic assumption Roussel (2006). Several approaches have been proposed to improve pressure prediction, including experimental measurements Trávníček et al. (2023); Gamil et al. (2023), analytical models Ovarlez and Roussel (2006), and numerical simulations Tichko et al. (2015). While analytical methods provide fast estimates, they rely on simplifying assumptions, and most numerical studies apply one-way coupling in which the concrete flow is solved independently and the resulting pressure is applied to prescribed formwork boundary, neglecting the influence of formwork deformation on the flow field.

Unlike one-way coupled numerical models, the two-way FSI formulation allows the deformation of the formwork to influence the flow field and pressure distribution, while simultaneously capturing the effect of the evolving concrete pressure on the structural response. The limitation of this approach can be addressed by a two-way fluid-structure interaction (FSI) model, in which the mutual interaction between fresh concrete flow and deformable formwork is explicitly taken into account. This article aims to develop a two-way FSI

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[1] Bc. Kryštof Kout: Department of Mechanics, Faculty of Civil Engineering, Czech Technical University, Thákurova 2077/7; 166 29, Prague 6; CZ, koutkrys@cvut.cz

[2] Ing. Jiří Němeček, Ph.D., Orcid 0000-0002-5635-695X: Department of Mechanics, Faculty of Civil Engineering, Czech Technical University, Thákurova 2077/7; 166 29, Prague 6; CZ, jiri.nemecek.1@fsv.cvut.cz

[3] Prof. Ing. Jiří Němeček, Ph.D., DSc., Orcid 0000-0002-3565-8182: Department of Mechanics, Faculty of Civil Engineering, Czech Technical University, Thákurova 2077/7; 166 29, Prague 6; CZ, jiri.nemecek@fsv.cvut.cz

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model for filling fresh concrete into the formwork while simultaneously capturing the real deformation of the formwork, which is essential for a consistent description of the casting process, particularly in cases where formwork deformability may alter pressure development.

2. Solution Strategy

The numerical analysis presented in this article is based on a coupled solution of fluid flow and structural deformation. Computational fluid dynamics is employed to model the flow of fresh concrete, while structural mechanics is used to describe the response of deformable formwork.

Fresh concrete casting into formwork represents a flow problem involving concrete and air. The evolution of the concrete during casting is described using a multiphase approach using the Volume of Fluid (VOF) method. In this formulation, each computational cell is characterized by a phase volume fraction, which implicitly defines the position of the interface. The fluid motion is governed by the incompressible continuity equation and the momentum balance, solved using mixture properties weighted by the local phase fractions. The momentum and continuity equations are defined as follows, respectively:

$$\frac{\partial}{\partial t}\left(\rho\vec{v}\right) + \nabla\cdot\left(\rho\vec{v}\vec{v}\right) = -\nabla p + \nabla\cdot\left[\eta\left(\nabla\vec{v} + \nabla\vec{v}^{T}\right)\right] + \rho\vec{g} + \vec{F}, \tag{1}$$

$$\nabla\cdot\vec{v} = 0. \tag{2}$$

where $\vec{v}$ is the velocity, t is the time filed, p is the static pressure, ρ is the fluid density, η is the apparent viscosity, g is the gravitational acceleration, and $\vec{F}$ is the force resulting from a sharp tension interface.

FSI describes problems in which fluid flow and structural deformation are mutually coupled. The fluid exerts forces on the structure, causing deformation, while the structural response modifies the fluid domain and influences the flow field. The linear momentum equation (equilibrium equation) in a structure is defined as

$$\int_S \sigma\cdot\vec{n}\,dS + \int_V \vec{f}\,dV = 0, \tag{3}$$

where σ is the stress tensor, $\vec{n}$ is the outward normal, S is the boundary surface and $\vec{f}$ is the body force vector acting over volume V. Accurate representation of such problems requires simultaneous consideration of both physical domains Richter (2017). The two-way FSI is solved using a partitioned implicit coupling approach where fluid flow and structure are solved separately and coupled iteratively through interface force and displacement exchange with the coupling procedure being schematically shown in Fig. 1.

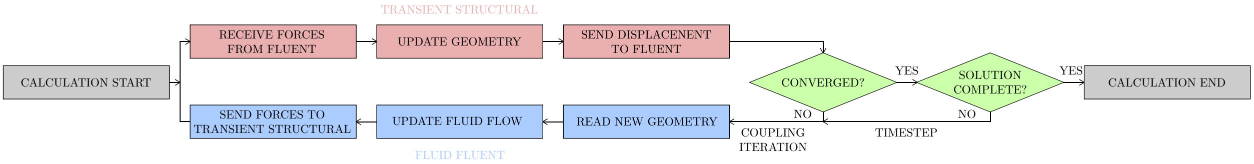

Fig. 1: ANSYS two-way coupling fluid-structure interaction flowchart.

3. Numerical two-way FSI Model

3.1. Geometry and mesh

A three-dimensional numerical model was prepared in Ansys Workbench 2023 R2. The model consists of two interacting domains: (i) a structural domain representing the formwork with dimensions of 100 × 400 × 2800 mm, and (ii) a fluid domain surrounding the formwork on both sides with a thickness of 100 mm. This configuration enables concrete flow on one side, where the inlet is located, while simultaneously allowing deformation of the formwork in the opposite direction. The geometry of the model is shown in Fig. 2a.

The fluid (Fig. 2b) and structural (Fig. 2c) domains are discretized independently, both using a quadrilateral mesh with a uniform element size of 50 mm. Additionally, the fluid domain is configured to allow dynamic mesh motion, enabling it to capture the formwork deformation obtained from the structural analysis.

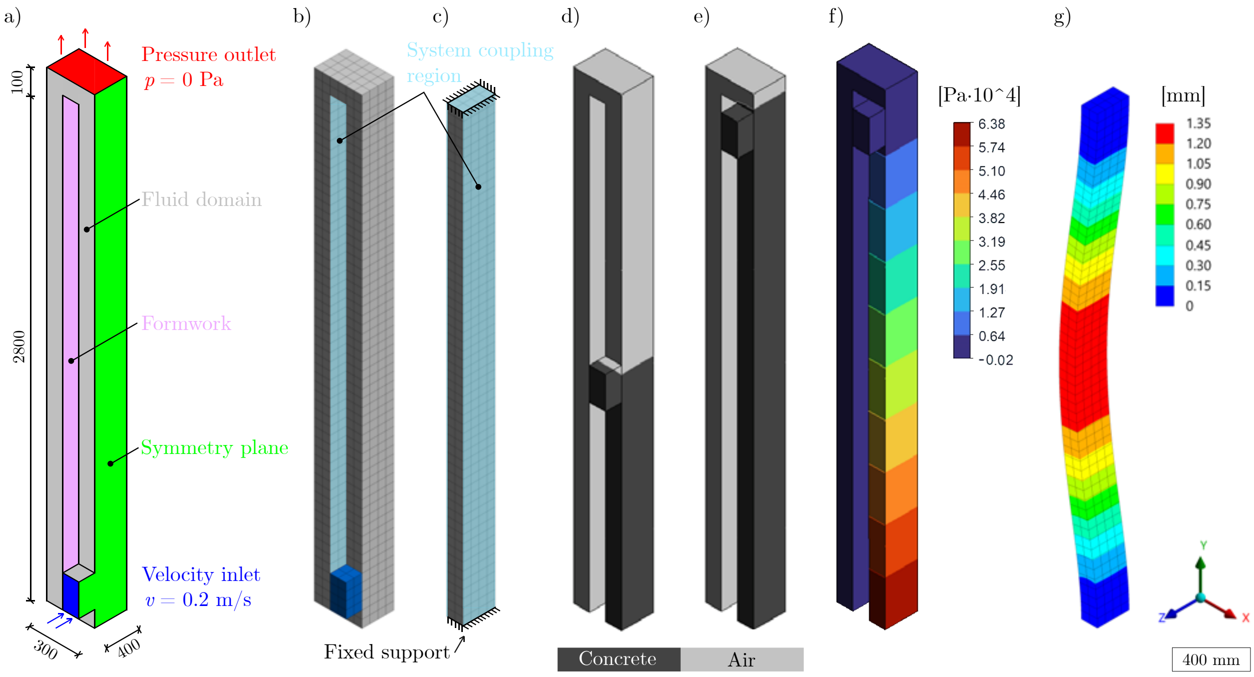

Fig. 2: Ansys model overview of a) boundary conditions, b) Fluent mesh, c) Transient Structural mesh, d) half-filled wall, e) fully filled wall, f) pressure results, g) deformation results.

3.2. Boundary Conditions and Materials

The formwork is modeled as an isotropic, elastic, deformable solid. The formwork material is characterized by a Young's modulus of $E = 43$ GPa, a density of $\rho = 425$ kg·m^{-3}, and a Poisson's ratio of $\nu = 0.3$, representing homogenized properties of wooden plates and steel rods chosen to match the global bending stiffness of a real formwork panel. A fixed support condition (zero displacements in all directions, SOLID186 elements) is prescribed at both the base and the top of the formwork. This boundary condition represents a stiffer support arrangement associated with additional reinforcement, such as formwork tie rods. The formwork surfaces in contact with the fluid domain are defined as system coupling regions (Fig. 2c), allowing bidirectional exchange of forces and displacements between the fluid and structural domains.

At the start of the calculation, the entire domain is filled with air. Fresh concrete is introduced through a user-defined function (UDF) coded moving velocity inlet at the base of the formwork at a constant velocity of 0.2 m·s^{-1}, corresponding to a typical casting rate in practice. To reduce computational cost, geometric symmetry is assumed and only half of the wall-fluid system is modeled. The top boundary is defined as a pressure outlet with zero gauge pressure to allow air evacuation during casting, while no-slip conditions are applied on all remaining solid walls. Gravitational acceleration ($g = 9.81$ m·s^{-2}) is included in fluid domain.

Fresh concrete is modeled as an incompressible non-Newtonian fluid using the Herschel-Bulkley model. The concrete density is set to $\rho = 2400$ kg·m^{-3}. The Herschel-Bulkley model parameters are defined by the yield stress $\tau_0 = 40.71$ Pa, consistency index $k = 0.93$ Pa·s^n, power-law coefficient $n = 1.45$ and critical shear rate $\dot{\gamma}_c = 0.5$ s^{-1}, corresponding to a real SCC mixture used in practice.

The transient simulation is carried out with a fixed time step of 0.1 s and a total simulation time of 150 s. Within each time step, 5 coupling iterations are performed until convergence of the exchanged interface quantities is achieved.

4. Results and discussion

The coupled two-way FSI simulation successfully captures the progressive filling of the formwork by fresh concrete during casting. The evolution of the concrete filling at selected time steps are shown in Fig. 2d and 2e.

The pressure distribution along the height of the formwork is dominated by the hydrostatic component $p = \rho g h$, which for the considered height corresponds to a maximum value of 65.92 kPa. The numerical results follow the hydrostatic trend closely, with small local deviations due to FSI interaction, and a maximum lateral pressure at the bottom of the concrete column of $p_{max} = 63.81$ kPa of the fully filled domain. For comparison, the maximum allowable pressure for standard formwork panels (e.g. PERI systems) is specified as 80 kPa. The obtained value therefore remains below this limit, indicating that the considered formwork configuration satisfies the strength requirement under the given loading conditions. The spatial distribution of lateral pressure obtained from the coupled two-way FSI analysis is shown in Fig. 2f.

The structural response of the formwork under lateral pressure is quantified by the displacement field, as shown in Fig. 2g. The maximum displacement occurs at mid-height of the wall and reaches a value of $u_{\max} = 1.35$ mm. Additionally, the model can be used to represent the effects of formwork tie rods, steel reinforcement during filling, formwork design variations, and interrupted concrete casting.

5. Conclusions

This article demonstrates the applicability of a coupled two-way fluid-structure interaction approach for the analysis of concrete casting into vertical formwork, forming a basis for further model development.

The results show that, although the maximum lateral pressure is largely governed by the concrete height, the coupled model enables simultaneous prediction of both pressure distribution and formwork deformation within a continuously deforming fluid domain. In contrast to simplified or one-way approaches, the presented formulation accounts for the influence of formwork deformation on the concrete flow itself, which allows a consistent description of pressure redistribution under different support conditions. Further improvement in prediction accuracy may be achieved by explicitly modeling individual formwork auxiliary components and by employing material models that capture the thixotropic behavior of SCC.

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