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Dynamic impact analysis of masonry buildings subjected to flood actions

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A B S T R A C T

The effects of floods on buildings described in terms of damage phenomena and collapse mechanisms are investigated. A comprehensive numerical approach simulating the fluid–structure interaction is herein proposed integrating (a) an ALE formulation, (b) a two-phase fluid flow, and (c) a refined finite-element structural modelling. Several potential structural failures are considered for the structure, whose activation conditions are discussed, in terms of both fluid and structural characteristics. A sensitivity study is performed in order to study the loading induced by the flood and the corresponding structural effects (e.g. internal stress/forces). A comparison between flood actions obtained through numerical simulations and with formulations available in literature is presented, with the specific purpose of emphasize the differences due to the dynamic amplification effects. As main novel results, dimensionless abacuses providing the structural safety factor as function of geometrical structural properties and inundation characteristics are provided. Such a result is very valuable both for researchers and practitioners in the field of flood risk assessment.

1. Introduction

Natural hazards such as flood events have caused loss of human lives and incalculable consequences such as damage of urban areas to both structures and infrastructures, heavy economic losses and difficult reconstruction processes [1,2]. Vulnerability and risk assessment of urban areas in presence of extreme flood actions is an emerging research field, especially in the last few decades, in which severe flood events cased disasters and extreme loading conditions [3].

However, the complete knowledge and prediction of the effects produced by natural hazards require advanced and sophisticated analyses, in which both hydrological and structural viewpoints should be considered [4]. The main purpose of the present study is to investigate the effects of the fluid action on conventional masonry structures, by means of comprehensive analyses in which FSI is accurately reproduced with respect to both space and time. The structural typology refers to classical masonry construction, which has been studied in different mountain regions of Europe to compute vulnerability functions for use in operational risk assessment.

Building behavior affected by flood actions can be considered as a multidisciplinary topic, in which structural and fluid mechanics are combined to reproduce fluid motion, pressure distribution and structural deformations under the effect of flood actions. Currently no omnicomprehensive model seems to exist. In the literature, the evaluation of structural damage produced by flood events have been described by empirical formulations based on stochastic models, developed on the basis of data extrapolated from aftermath survey and insurance claims [5]. In this framework, food damage estimation on building structures is typically described by means of Depth or Velocity Damage Functions (D-V-DF), in which empirical relationships between expected flood depth or flow velocity and the estimated damage are considered in the analysis. Damage assessments could be described by economic or monetary concepts, i.e. ratio between costs of repair to the market value of building [6] or, in general, introducing other costs such as for instance those obtained from the flood risk management or reconstruction process [7]. Such vulnerability models strictly depend from the definition of the initial data, in relationship to the arbitrariness in the post event data collection, which may produce quite variable evaluations [8]. Alternatively, synthetic vulnerability models are developed consistently with expert-based approaches, which use damage data collected via what-if-questions [9]. Although such approaches do not require any data from the flood event, high efforts are necessary to achieve information for each category or building typology [4]. Moreover, results, obtained in this framework, produce uncertain damage estimates [10], in relationship to the heuristic or empirical characteristics of the methodology. It is worth noting that since the flood events are investigated on different spatial scales, ranging from micro to macro, the definition of the damage function at the building or infrastructure level may influence the analyses at the larger scales. Therefore, deterministic vulnerability models based on analytic or numerical

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formulations, which identify the damage behavior of the structure, are much required for the assessment of the flood events. In the literature, very few attempts are developed to quantify the building vulnerability by using analytical models, in relationship to the multitude of damage processes, which affect the structures when subjected to flood events. Most of the formulations are based on conceptual engineering models, which quantify vulnerability of residential building, including relevant flood characteristics, such as water depth, flood rise and duration and debris flow [4,11]. In such analyses, the failure behavior of structural elements at risk is described in the terms of the design strength of the materials, depth and speed of the fluid flow. A generalization of previous models, including an unified formulation at building scale by using engineering models, was found in [12], in which vulnerability curves in terms of damage ratio, i.e. ratio between monetary loss and component value, were derived. Structural capacity of non-engineered masonry structures was analyzed in [13], by means of an efficient probability-based design formulation, in which an incremental flood height analysis is implemented to identify the structural performance as a function of increasing water height. Moreover, structural response of masonry constructions subjected to debris actions was analyzed in [14] in which damage description is defined in terms of demand/capacity values for a single wall panel of the structure. In such analysis, the damage mechanisms in the structure are modeled by using a FE approach based on shell elements. The failure conditions are assumed to be produced by hydraulic and debris flow actions described by means of drag coefficients and an equivalent pseudo-static formulation. In most of the models described above, the structural vulnerability of building in flood flows is modeled as a function of the water depth and flow velocity. The flood damage analysis is identified with respect to three levels of damage analysis [15] ranging from the macroscale or mesoscale, for national and regional studies, to microscale, at building level. Although, a generalized multiscale model should be implemented to fully identify building vulnerability under flood actions, such approach is affected by intrinsic complexities to be handled. Therefore, uncoupled formulations in different scales are typically preferred, in which macro/mesoscale analyses are based on the results obtained at building microscale level. As a consequence, it appears to be quite reasonable that the results at lower scale may have a notable influence on the results obtained at larger scales [16]. Therefore, an accurate analysis at microscale becomes quite important to identify properly the damage effects produced by flood actions. However, in the literature, the totality of the flood models utilizes pseudo-static approaches to reproduce the hydrodynamic actions, neglecting fluid-structure interactions during the flood events and the dynamic effects produced by fluid motion. A quite comprehensive study is developed in [17], in which a numerical evaluation on the tsunami debris impact loading on structural walls is proposed. The actions produced by the fluid flow in terms of pressure distribution are quite dependent from the Froude number, which identifies the characteristics of wave reflection and the impact of the fluid front against the structural system [18,19]. Moreover, the structural analysis is typically restricted to assess ultimate limit states concerning the strength and deformation of structure, consistently to design prescriptions obtained by current design codes [20]. Such approach typically refers to structural schemes, which do not simulate the global behavior of the structure, but only small portions, introducing in the fluid-structure description quite important simplifications.

For these reasons, in the present study, an accurate description of the FSI behavior is developed with the purpose to quantify the dynamic amplification effects produced by the fluid motion on the structural system. Moreover, a parametric study in terms of fluid and structural characteristics is developed to identify depth-speed damage curves. Finally, comparisons with existing formulations based on a pseudo-static approach are proposed. The outline of the paper is as follows. Section 2 presents the formulation of the governing equations for the fluid/interaction problem and coupling conditions, whereas in Section 3 damage definition for the structural system is reported. Finally, the numerical implementation is reported in Section 4, whereas comparisons with pseudo-static approaches and parametric results to investigate the dynamic amplification factors are proposed in Section 5.

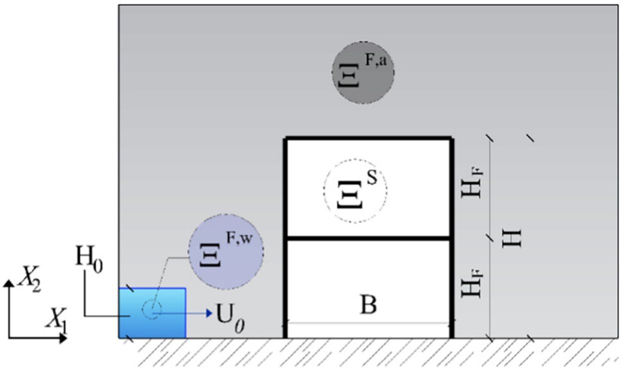

Fig. 1. Schematic representation of the fluid and structural geometries and coordinate systems.

2. Numerical methods and computational framework

In order to simulate the Fluid-Structure Interaction (FSI), the general domain Ξ is assumed to be composed of two different subdomains occupied by the fluid and the structure, i.e. Ξ^F or Ξ^S respectively with $\Xi = \Xi^F \cup \Xi^S$. Moreover, the fluid system is assumed to be described by two immiscible fluids, which consist of water (phase 1, $\Xi^{F,w}$) and air (phase 2, $\Xi^{F,a}$). The FSI model is based on a 2D plane domain, in which the two fluids interact and produce actions on the structure. The building is assumed to be symmetrically loaded with symmetric mechanical and geometric properties. Therefore, the structural behavior is essentially 2D, but it is modeled by tridimensional shell elements to correctly distribute the actions produced by the flood events in each element of the structural system. A schematic representation of the fluid and structural models is reported in Fig. 1.

2.1. *Fluid flow and structural behavior*

In the present study, fluid and structural systems are coupled by means of the ALE methodology, which allows to simulate fluid motion, fluid/structure interface and path-following nature of the applied loads on the structural system [21]. In particular, the structural deformations are produced by hydrodynamic actions of the fluid motion on the fluid/structure interface. However, the fluid domain is affected by the structural deformations, which basically produce moving wall boundary conditions with displacement and speed fields coinciding with those of the structural system. The motion of the fluid particles is described by introducing a fictitious reference system, known as "*referential coordinate system*", whose evolution is typically arbitrary and it does not coincide with that defined in either Lagrangian or Eulerian coordinate systems. In particular, as shown in Fig. 2, for each time belonging to $t \in [t_0,\Upsilon]$ with Υ the time observation range, a family of mapping function $\underset{\sim}{\zeta}$ associates a point $\underset{\sim}{r}$ of the referential configuration Ξ_0 to a point $\underset{\sim}{X}$ in the current domain, as follows:

$$\underset{\sim}{\zeta}\colon \Xi_0(t_0) \to \Xi(t), \quad \underset{\sim}{X} = (\underset{\sim}{\zeta},t) \tag{1}$$

where $\underset{\sim}{\zeta}$ is assumed to be an homeomorphism, that is $\underset{\sim}{\zeta} \in \overline{\Xi}_0$ invertible with continuous inverse $\underset{\sim}{\zeta}^{-1} \in \overline{\Xi}_0$. Moreover, the derivative of the velocity with respect to the time or the spatial field of the fluid particle $\underset{\sim}{U}$, with $\underset{\sim}{U}^T = [U_1\ U_2]$, at a generic coordinate $\underset{\sim}{X}$ and time t of the reference frame is expressed as follows [22]:

$$\frac{d\underset{\sim}{U}}{dt} = \frac{\partial \underset{\sim}{U}}{\partial t} + \nabla_{\underset{\sim}{X}} \underset{\sim}{U}\cdot(\underset{\sim}{U}-\underset{\sim}{V}) = \frac{\partial \underset{\sim}{U}}{\partial t} + \underset{\sim}{J}^{-1}\nabla_{\underset{\sim}{r}} \underset{\sim}{U}\cdot(\underset{\sim}{U}-\underset{\sim}{V}) \tag{2}$$