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RESILIENCE OF STRUCTURES AND INFRASTRUCTURE UNDER EXTREME TRANSIENT LOADS

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Abstract. In this work we address the challenge pertinent to validating resilience of large engineering structures, both in terms of integrity to failure and ability to recover under extreme transient loads. Of particular interest are the effects of combined transient loads in industrial domains, such as civil and mechanical engineering. The effect of combined extreme transient loadings on a structure is not well understood— whether the source is man-made, such as an explosion and fire, or natural, as an earthquake or extreme wind loading. A critical assessment of current knowledge is timely (with Fukushima-like disasters or terrorist threats).

The central issue in all these problems is structural integrity, along with their transient nature, their unexpectedness, and often the uncertainty behind their cause. No single traditional scientific discipline provides full answer, but a number of tools need to be brought together: nonlinear dynamics, probability theory, some understanding of the physical nature of the problem, as well as modeling and computational techniques for representing inelastic behavior mechanisms. The paper also covers model building for different engineering structures and provides detailed presentations of extreme loading conditions. A number of illustrations are given: quantifying a plane crash or explosion induced impact loading, quantifying the effects of strong earthquake motion, quantifying the impact and long-duration effects of strong stormy winds — along with a relevant framework for using modern computational tools. The proposed approach considers the levels of reserve in existing structures, and ways of reducing the negative impact of high-risk situations by employing more sound design procedures.

Keywords: massive structures; infrastructure; damping; multiscale models; transient loads; probability effects;

1. Introduction and Motivation

This paper deals with important challenge on validating the durability and lifetime integrity of massive composite structures under extreme transient loads. The illustrative examples concern: earthquake, airplane impact, fires or tsunamis (see Figure 1). Special attention is given to costly massive structures or infrastructure with 'irreplaceable' components, which are characterized by a number of different failure modes that require the most detailed description and interaction across the scales. We would like to significantly improve the currently dominant approach of mode superposition, which is applicable when there is a linear relationship between external forces and corresponding structure-infrastructure response.

The key issue we address pertains to use of the material damage as the source of damping. Here, one needs to define nonlinear inelastic models, which pertains to any particular material. It can accommodate any among the most frequently used materials in engineering applications, such as steel, concrete and masonry. We conclude with clear recommendations on how to define the damping forces. Usual damping capacity is defined as the damping ratio of the energy dissipated in one cycle of oscillation to the maximum amount of energy accumulated in the structure, with viscous nature of damping forces. An alternative advocated here is to use the material damage and interface damping, much dependent upon the type of material, as well as on manufacturing method. By taking into account that the material characteristics vary due to material heterogeneities, which can be described by replacing the material parameters with random variables of random fields. Such a coupled nonlinear mechanics-probability computations provide the reliable estimation of influence that the material damage can have on structural damping, leading to the same asymptotic response as viscous damping, but described with much more reliable path to constructing predictive models. This is illustrated for some of the most frequently used structure materials.

Fig. 1 Three examples of extreme natural and man-made hazards studied by PI: a) failure of Tacoma bridge; (nested parallel) fluid-structure computations of flutter-instability produced by forced long-term oscillations induced by wind (Ibrahimbegovic 2014); b) Impact by tsunami of Samoa island; model quantifying impact on a structure by water column (Ibrahimbegovic 2014); c) Terrorist threat for NPP structure under impact of large airplane; model quantifying damage to structure due to airplane crash (Ibrahimbegovic 2009a).

2. Main Objectives

The main objective in better damage and failure modes interpretation is development of novel Mesh-in-Element (MIEL) Multiscale Method capable of representing strain field heterogeneities induced by evolution (and interaction) of localized failure mechanisms in massive structure, pertaining to micro scale (FPZ-fracture process zone), macro scale including softening (macro cracks) and non-local macro scale (bond-slip for long fiber reinforcement). The objective of MIEL Multiscale Method is also to provide capabilities for quantifying the risk of premature localized failure through probability description of initial defects (microstructure heterogeneity) and uncertainty propagation through scales. The novel scientific concept to be explored pertains to multiscale formulation and solution of coupled nonlinear mechanics-probability problem replacing the standard homogenization approach that can only provide average (deterministic) properties of heterogeneous composites. This concept is of interdisciplinary nature with Mechanics (defining probability distribution) and Applied Mathematics (providing uncertainty propagation) combined in order to capture the influence of heterogeneities and fine scale defects on premature failure.
The most important challenge concerns the ability to provide the sound, probability-based explanation of damping exponential asymptotic decay at the structural level, without resorting to classical viscous model but with different failure modes observed for different size specimens and real structure heterogeneities typical of composite materials (see Figure 2).

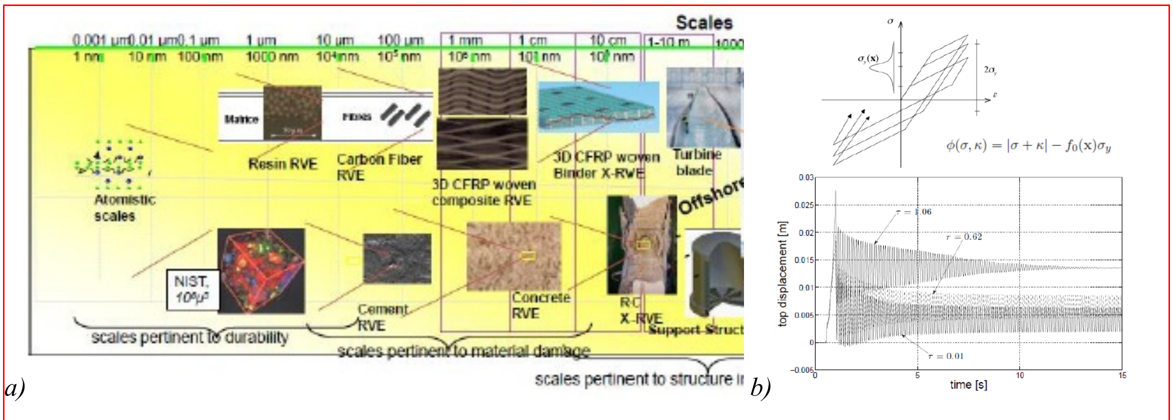

Fig. 2 Mesh-In-Element (MIEL) multiscale method – a) failure modes for 3D carbon-epoxy woven composite and for reinforced concrete; b) hysteresis loops for heterogeneous materials with material parameters probability distribution described by random fields, producing the structural response

characteristic of exponential asymptotic decay.

3. Concluding remarks on current and future research

The biggest potential gain concerns changing the resilience validation procedures for massive structures that are beyond the size suitable for testing at present. The scientific gains concern providing the Mesh-in-Element (MIEL) Multiscale Method that connects computations with design studies (optimization), testing (identification) and safety verification (monitoring) of massive composite structures. The scientific gains also concern further placing the proposed method within multiphysics framework, along with the original use of goal oriented error estimates to provide sufficiently reliable interpretation of extreme conditions (e.g. fluid or heat flow) and the code-coupling software implementation to quickly integrate existing simulation codes within such a framework.

The main technological gain is in development of the open source computational tools that can speed-up testing, innovation and decision-making in complex composite systems. Of special interest is the strategy that allows integrating the existing legacy software products that are used to verify and validate safety of particular components assembled within such complex systems. There are multiple challenges in solving any such problem pertaining to: theoretical formulation, discrete approximation, algorithmic stability and robustness, and finally informatics developments capable of integrating existing legacy codes.

Further details on point of departure in the current research and developments to follow are given in our recent works (Ibrahimbegovic et al. 2003a, 2003b, 2003c, 2003d, 2004, 2005, 2007, 2008, 2009a, 2009b, 2009c, 2010a, 2010b, 2011, 2012, 2014, 2015, 2016, 2017, 2018, 2019).

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