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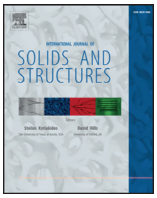

Structural behavior of a metallic truss under progressive damage

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ABSTRACT

Modern requirements on constructions impose that proper design strategies must be adopted in order to obtain a robust structure: in this sense, consequence-based design focuses the attention on the structural response to damage. The behavior of statically indeterminate structural systems under damage is non-linear because the load paths intertwine each other, even if each component behaves linearly. The paper aims both to highlight the behavior of a metallic truss under progressive damage and to define a possible strategy for designing a truss that is able to sustain damage acting at random on one of its elements. Structural complexity is used as a leading parameter. Following the results of a parametric analysis, it emerges that, as much as the Normalized Structural Complexity Index increases, the efficacy of the load paths is spread such that the impact of random damage decreases, making the approach feasible.

1. Introduction

The modern requirements in structural design impose that a structure has to be robust. Many definition of structural robustness have been formulated. ISO (1998) considers the possibility of a structure not to be damaged to an extent disproportionate to the original cause. The Eurocode proposes a similar idea, considering the ability of the structure to withstand events, instead of being damaged (CEN, 2006). The American General Services Administration proposal relates to the concept of the resistance to damage without premature and/or brittle failure (ARA, 2003). The Joint Committee on Structural Safety's document proposes an approach based on risk at a damage state (JCSS, 2011). Many authors have dealt with the concept of robustness proposing various properties that define a structure as robust (Agarwal and England, 2008; Biondini et al., 2008a; Bontempi et al., 2007; Starossek and Haberland, 2011; Val et al., 2006). Vrouwenvelder (2008) states that a robust structure should not be too sensitive to local damage, whatever the source of damage.

In the majority of the ideas previously reported, the concept of damage represents the central idea, i.e., it plays a fundamental role. The actual design approach considers, first, the set of external forces acting on a structure and combines their effects in order to get a spectrum of actions on each element. The structural safety is thus assessed through a reliability-based approach. The preceding approach is not adequate for considering the possibility of progressive collapse, i.e., accounting for robustness. Starossek and Wolff (2005) criticize the assumption that low probability events and unforeseeable incidents (accidental circumstances) need not be taken into consideration in the design, while they are the most dangerous for the construction.

The philosophy to be followed in the design of a structure robust against damages differs from what is usually done. The idea of implementing a design based on the consequences rather than on reliability takes its origins at the beginning of the new millennium. In a conference held at the University of Notre-Dame, IN, Abrams et al. (2002) coined a new term: consequence-based engineering. Despite the fact that they relate the idea to seismic risk, the approach was outlined in its essential aspects. The so-called consequence-based design is composed by an iterative assessment of the consequences of a damage: if anticipated consequences exceed tolerable ones, redesign is necessary until the trend is opposite. The consequences can be estimated for a number of different system-intervention strategies with various input parameters describing the hazard or the built environment (Abrams, 2002).

The concept of damage is, in itself, non-trivial. It can be considered as an unplanned variation of the properties (Mises, 1923) or of the geometry of one or more parts of a structure that entails a weakening and, usually, negative consequences. The methods usually used in the evaluation of damage on a structure consider its static or dynamic response (Andreaus and Baragatti, 2009; Andreaus et al., 2007; Roveri and Carcaterra, 2012), or both (Irschik, 2002). Yao et al. (1986) underlined the fact that the causes of damage can be various: material, structural configuration and construction, loading conditions. Environmental conditions might

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play a relevant role as well (Cennamo et al., 2014; De Biagi and Chiaia, 2013a). The previous observations can be related to any kind of civil structure. Steel structures, such as reticular masts, bridges, and long-span beams, are prone to be subjected to damages with the possibility of local and global collapses Biondini et al. (2008b). In a society in which anthropogenic hazards are possible, in recent times, specific attention has been paid to the response of structures to unexpected events, e.g., terroristic attacks. These scenarios are unforecastable and the basic hypotheses of reliability-based design are false since the probability of occurrence of the cause of damage is not known *a priori*.

The present paper addresses two important issues. The first relates to the behavior of a truss under progressive damage. In the framework of structural robustness, the relationship between the damage and the structural response would increase the possibility to assess the presence of damage in the structure as long as the damage phenomenon acts on it. The second investigates the possibility to design a truss structure that is able to sustain damage acting at random on one of its elements.

In the present paper, the concept of structural complexity is used. Although a general treatment on the topic is available in De Biagi (2014), a short theoretical reminder is presented in Section 2. Simulations on a sample truss cantilever are illustrated in order to respond to the addressed questions: Sections 3 and 4 detail the calculations and the results, respectively. The results are discussed in Section 5. The approach herein proposed might be implemented in the preliminary steps of a design process. It explores the possibility of increasing the damage-tolerance of the structure by optimizing the variety of load paths under a specific loading scenario.

2. Theoretical background

Two parameters are used throughout the paper. The first accounts for the distribution and the efficacy of the load paths in the structure. The second is related to the behavior of a damaged structure, as detailed in the following.

2.1. Structural complexity

The use of graph theory in the field of structural engineering dates back to the Fifties. The first applications of topology and graph theory to structural mechanics are due to Carter and Kron (1944) and Kron (1962), who first made an explicit analogy between electrical networks and elastic structures. In the same period, Langefors (1950, 1956a, 1956b) presented a framework for the analysis of statically indeterminate continuous frames by means of algebraic graph theory. An alternative approach was proposed by Samuelsson (1962) for skeletal structures, and Wiberg (1970) for continuum problems. Henderson and Bickley (1955) related the degree of static indeterminacy of a rigid-jointed frame to the First Betty Number and Kaveh (1988) applied many graph theoretical concepts to structural mechanic and, in particular, to structural optimisation (Kaveh, 2004). Others applications of graph theory to elastic systems can be found in Kaveh (2006).

In mathematics, Rashevsky (1955) introduced the notion of topological content, which was formalized by Mowshowitz (1968) through the concept of graph entropy. Following that, the interest for information-theoretic network complexity increased and the concept of graph entropy was applied to many disciplines (Dehmer and Mowshowitz, 2011; Mowshowitz and Dehmer, 2012). In recent times, a generalized framework for network complexity was proposed (Dehmer and Mowshowitz, 2010).

Recently, De Biagi and Chiaia (2013a) defined a complex structure as a system made up of a large number of parts that interact in a non-simple way under an arbitrary loading scheme. This definition, following the work by Simon (1962) in other disciplines, accounts for the shape of the structure, its stiffness, and the acting loads. The metrics for determining the structural complexity are based on the so-called Information Content introduced by Shannon (1948) and implemented in the researches on graph entropy previously recalled. Here, the information content is represented by the effectiveness of the load paths across the truss. A simple structure is the one that has a reduced number of effective load paths. On the contrary, when all the possible load paths are equally effective, the structure reaches its maximum complexity (De Biagi, 2014).

A path for the loads between the elevation nodes and the foundation ones is conceptually materialized as a fundamental structure, i.e., a link between the elevation and the foundation. The load path, and thus a fundamental structure, is determined through the law of statics. In truss structures, a fundamental structure is a statically determinate scheme of rods that spans all the nodes and is made of a subset of rods of the reference truss. In frame structures, the fundamental structures were originated from cuts turning the frame into a tree-like structure. Herein, the extraction of fundamental structures from a statically indeterminate truss is performed through the alternate removal of rods.

The elastic energy, or the deformation work, is the parameter that better describes the behavior of a structure subjected to loads. First, it accounts both for stiffness and loads, and, in case of nonlinear analysis, it considers the ductility of the elements composing the structure. The effectiveness of a load path, identified through the fundamental structure, is measured as the ratio between the deformation work in the reference structure and the one performed on the fundamental structure. This ratio is called the performance ratio ψ and ranges from 0 to 1 since the denominator is always larger than the numerator. If the deformation work of the fundamental structure is close to the one of the reference, the load path results effective; if the deformation work of the fundamental structure is significantly larger than that of the reference scheme, the ratio tends to zero, meaning that the load is not effective, i.e., not representative of the overall behavior of the statically indeterminate structure. The number of fundamental structures and, consequently, of performance ratios, n, depends on the original scheme. The measure of the “amount” of information required to describe the structural behavior, is based on the definition of information entropy stated by Shannon (1948). In particular, the Structural Complexity Index SCI, is represented by

$$\mathrm{SCI} = -\sum_{i=1}^{n} \left(\frac{\psi_i}{\sum_{j=1}^{n} \psi_j} \log \frac{\psi_i}{\sum_{j=1}^{n} \psi_j} \right), \tag{1}$$

where ψ_i is the performance ratio of the i-th fundamental structure, as defined previously. The base of the logarithm is not relevant (if 2, the measure is in bit). The entropy measure possesses many interesting properties (Gray, 2011). The identification of the load paths can be easily performed if the structural scheme is studied under the framework of Graph Theory (De Biagi and Chiaia, 2013a).

In order to compare the complexities of various structures with different sizes and element numbers, a normalized parameter is introduced. The SCI is divided by its maximum possible value, which represents the situation in which each possible load path has the same effectiveness (i.e. the same performance factor). This situation, representing the maximum complexity, corresponds to a SCI equal to $\log n$, where n is the number of fundamental structures (load paths). Thus, the Normalized Structural Complexity Index, NSCI, is expressed as

$$\mathrm{NSCI} = \frac{\mathrm{SCI}}{\log n}. \tag{2}$$

The NSCI ranges between 0 and 1. As much as the parameter approaches to 0^+, the structural system is simple. On the opposite