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Resilience: Theory and metrics – *A metal structure as demonstrator*

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ABSTRACT

The paper develops a theoretical model and metrics for structural resilience. It addresses the general case of physical systems after they suffer damages due to natural or industrial hazards. They may suffer serious physical damages and may generate also social and economic losses. Depending on the interaction between the sub-systems and individual components, it may be possible for the system to absorb the damage, remain on service and recover. The method addresses the utility functions (resistance), damaging sequences, residual state, post-event capacity, recovery functions and resilience metrics and indicators. It becomes then possible to identify whether a structure is "objectively" resilient or not, under a given set of conditions. A simple metal structure relying on a full support is adopted as demonstrator. The resilience indicator expresses the residual capacity under bending effects of the system, when subject to uniform lateral load and initial damage of the critical cross section (at beam support). Due to plasticity, it is shown that the system can recover and be resilient as long as the damage does not exceed 18.4% of the cross critical section. Subdomains for resilience are also easy to identify in the [hazard, vulnerability, damage] operating space for the case study.

1. Introduction

The resilience is nowadays considered as a reference concept when dealing with disasters, damages and post-disaster recovery or management. Actually, since its first definition, in 1904 in engineering sciences (Charpy's specimen test), as the residual bearing capacity for a metal specimen to stand future loading (shock) after it suffers a prior section loss (partial damage), it has been adopted and adapted to various scientific fields. In fact, each scientific discipline which adopted this concept has developed adaptations according to its specific needs: specific objects, specific hazards, specific vulnerability, damages or trauma, post-disaster management or recovery. Thus, the resilience is either described in qualitative terms (case of social or human sciences) or quantified by specific metrics (case of biology, medical, economy and engineering sciences):

- Structural, urban, systems and risk engineering as well as critical infrastructures [3,5,9–13,15–17,20–21,25,30–33,36, 39–41,45,50,52,55]
- Life sciences, ecology, medicine [10,18–19,22,34,37,43–44,49, 54,56–57]
- Disaster management and analysis or policy [1,6,23,28–29, 46–48]
- Economy, business, logistics [2,4,7–8,26,27,35,42]
- Social and human sciences, psychology [14,24,38,51–53,57–58].

However, there is still a lack of unified and quantified framework to describe the resilience through consensual metrics and utility functions.

The challenge, when facing natural and industrial disasters, is then to adopt a relevant and consensual methodology able to mix qualitative as well as quantitative resilience metrics or indicators: physical systems such as constructions, infrastructures and lifelines as well as social or economic aspects. In fact, there are physical and/or socio-economic interactions between elementary components in a construction, urban set or country, for instance. The damage caused to one component will therefore affect the other components.

The resilience concept can then serve as an integrated and unified framework able to describe the damages caused to a system and its components, the damages' influence on conventional utility functions (physical or socio-economic) as well as the available processes and resources that may help the system recover and survive. Though there exist various indicators that are helpful to describe qualitatively the resilience [13], it is still challenging to develop quantitative measures and indicators in order to identify whether an urban set is resilient against a given potential hazards, for instance.

The purpose, in the present paper, is to discuss the main parameters which influence the resilience. It also aims to propose

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objective metrics or indicators able to identify quantitatively whether a system is resilient. A metal structure is then adopted as demonstrator for the proposed framework.

2. Theoretical approach for resilience and its metrics

2.1. System, damage and resilience – General concepts

Under given conditions, a system may be damaged by occurrence of natural, technological or industrial hazards. For instance, tanks in industrial plants may be damaged by earthquakes, tsunamis, floods, blast waves or fragments impact due to explosions, thermal flow and fires. Consequently, the mechanical damage can be very important, may cause product leakages and may lead to cascading events (domino effect) with interruption of the industrial activity. Sometimes, it is also possible to strengthen or repair the damaged components so that the industrial activity recovers its capacity and remains in service. For this purpose, its residual state and its post-event (accident) capacity need to be described by utility functions which may concern its mechanical resistance, serviceability, or any other requirement expected to be fulfilled by the system. A new trend in risk and post-disaster analysis focuses on resilience issues. The resiliency deals with the fact that a system, impacted by a hazard effects, should not only resist by standing to the hazards and suffer damages, but it should also recover or be strengthened to return within a given period time into acceptable levels of use and serviceability.

Though there is still a lack of consensual metrics and indicators, it seems obvious that any relevant quantitative resilience analysis should require the prior definition of key parameters, see Fig. 1 ([30–32,37,39–42,47–50,54–55]):

- The utility function or resilience index which describes the system capacity. In this study, for instance, the utility function will concern the mechanical bearing capacity of metallic tanks considered as physical systems for demonstration and illustrative purposes.
- The *survival* threshold value of the resilience indicator (R_{min}) below which the system is considered as *non-resilient*.
- The optimistic or optimal value of the resilience indicator (R_{opt}) above which the system is considered as *supra-resilient*, i.e. case of over designed systems.
- The optimal resiliency interval [R_{min}; R_{opt}], within which the system is considered as *resilient*.
- The initial instant of severe damage occurrence (t_d) due to any of the potential hazards, natural or technological
- The damage (D) caused to the system expresses the loss of its utility function. By convention, its values could range within the interval [D = 0: no damage; D = 1: total damage].
- A reference time period (T_{ref}) during which the system should be able to recover or transformed in order to meet new requirements. In general, at post-disaster stage, the utility function can either decrease (system state is worsening as it is the case for softening materials) or increase (system state is strengthening and recovering as it is the case for hardening materials). It may happen also that the system state remains in a stable and constant state, with a constant residual utility function. In case the resilience index value remains below the minimal threshold value (R_{opt}) during the period [t_d; T_{ref}], the system is then considered as *non-resilient*. Otherwise, it is *resilient*.

Therefore, it is obvious that the resilience analysis should investigate how a complex system will be damaged. After it is damaged, the analysis should also investigate how it can recover or go into worse conditions. Furthermore, its final bearing capacity or resilience indicator will intimately depend on available resources and interactions for exchanges between its constitutive components or at its frontiers from external systems.

For illustrative purposes, the present study investigates the resilience of metallic structures such as tanks (cylindrical forms), pipes (cylindrical tubes) and beams (rectangular cross area). They are supposed to be subject to lateral loadings as it could be the case under tsunamis, floods and blast waves, for instance. Sensitivity analysis is performed in order to study the resilience for various values of the damage and various forms of the post-damage evolution function: worsening, strengthening or stationary conditions. This case study will be used as demonstrator for the application of the integrated framework developed and proposed for quantitative evaluation of the resilience by:

- Defining the utility function and an objective resilience index,
- Considering various limit conditions and various interactions between the constitutive parts of the system in order to describe the recovery at post-damage stages,
- Considering various values of initial damages in order to investigate the post-damage evolution and the possible return to required values of the utility function, and

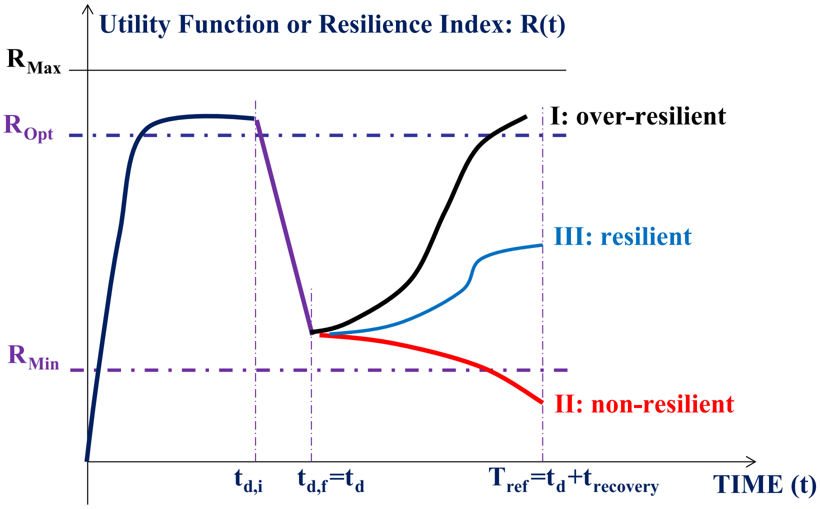

Fig. 1. Resilience evolution vs. time.