

Structural Resilience through Structural Health Monitoring: A Critical Review

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Section 1.2

Structural Resilience through SHM: a critical review

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The manuscript presented herein aims to evaluate the structural resilience improvements based on Structural Health Monitoring. The entire document is organized into two main parts. In the first one, the key stages of the monitoring method are described at varying degrees of difficulty and knowledge level. A brief digression of the established and cutting-edge approaches that may be traced back to the discipline is also included. Next, structural resilience and its dimensions are described by referring to the literature. At the end of this general discussion concernith the theoretical aspect of these disciplines, a bibliographical and bibliometric study of the references has been conducted and the relationship between monitoring and resilience has been identified. In this way, any conceptual and practical link present in the existing literature will be highlighted.

The second part of the chapter is devoted to the analysis of the conceptual relations between the four dimensions of structural Resilience and the four stages of the Structural Health Monitoring discipline. Schemes and examples are provided in this chapter to demonstrate how information at each monitoring stage can be employed for the evaluation of the corresponding resilience dimension.

1.2.1 Structural Health monitoring and Resilience: State-of-Art

1.2.1.1 Structural monitoring for damage diagnosis and prognosis

Different types of degradation, such as long-term corrosion or fatigue, as well as transient occurrences like earthquakes, can cause damage to civil engineering structures. Damage diagnosis allows informing decision-makers about the appropriate response action to hazardous

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structural situations. The foundation phases of Structural Health Monitoring (SHM) for damage diagnosis are damage detection, localization, and quantification. The ultimate phase, or the final SHM objective, is the damage prognosis, or the estimation of the system's remaining life, given the measurement and evaluation of its current structural status (Doebbling et al. 1998; Faravelli & Casciati 2004; Cheung et al. 2008; Domaneschi et al. 2013, 2017; Morgese et al. 2021). In detail, the four phases can be characterized as follows (Doebbling et al. 1998):

- **Phase 1:** Establishing whether there is damage to the structure.
- **Phase 2:** Phase 1 plus locating the damage's geometric position.
- **Phase 3** includes Phase 2 as well as a measurement of the extent of the damage.
- **Phase 4:** Phase 3 plus an estimation of the structure's remaining useful life.

The first two phases represent the main supports offered by the most common vibration-based damage identification techniques (without the use of structural models). In some circumstances, Phase 3 damage identification can be achieved by combining vibration-based techniques with a structural model. Phase 4 remains a challenging problem for engineers, which requires multidisciplinary and predictive modelling capabilities, and it could provide invaluable safety and economic benefits in structural and infrastructural management.

Doebbling et al. (1996) provide a survey of the literature on the various techniques for identifying damage and monitoring the health of structures based on changes in their measured dynamic parameters. They are methods based (i) on the modification of the modal characteristics, (ii) on the changing of dynamic flexibility, (iii) on the updating of structural matrices under constrained optimization, but also on (iv) nonlinear approaches, and (v) methods based on neural networks. As a result, they are divided into groups according to the type of measured data that was used, and/or to the technique for determining the damage from the measured data that is implemented. A dataset of the undamaged structure is assumed by many methods, while others involve a thorough FEM of the structure. Frequently, the

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unavailability of this kind of data can make a method impractical for some applications. Although there is no guarantee that dependency on numerical models and historical data can be eliminated, steps can and should be taken to reduce it.

Focusing on the more recent developments in the field, SHM systems have undergone substantial developments due to emerging computing power and sensing technology, which have thus enabled numerous installations on various civil infrastructures for structural health assessment, to detect damage or anomalies, by exploiting continuous monitoring of environmental conditions, loads, and, most importantly, structural responses. As a result, the number of sensors in an SHM system has increased as, of course, the number of data collected, which has reached enormous numbers. To handle this large amount of data, advanced processing methods had to be employed to convert the collected data (heterogeneous and multi-source) into different types of specific useful indicators for making effective inspection, maintenance and management decisions. Consequently, the use of automatic algorithms for data management, computation and structural (e.g., damage) identification has become increasingly popular in the scientific community. With elegant performance and frequently rigorous accuracy, machine learning algorithms, especially deep learning algorithms, have become increasingly practical and widely employed in vibration-based structural damage diagnosis. Unlike the second, which can identify a direct mapping from the raw inputs to the final outputs without the requirement for feature extraction, the first requires preprocessing data samples to extract certain features or attributes that reflect the most distinctive pieces of information. When it is difficult to manually select a new good group of features to be used for training the system, deep learning algorithms are of utmost relevance. As a result, deep learning is regarded as a branch of machine learning, and numerous platforms have successfully used it to deal with large amounts of data (big data). Fortunately, deep learning and developments in parallel computing have both been successfully used in several applications, in a wide range of

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research areas, as SHM (Ye et al. 2019; Azimi et al. 2020; Sun et al. 2020; Avci et al. 2021).

1.2.1.2 The four dimensions of structural resilience

When a structure is hit by a severe event, it can develop a certain level of damage: its ability to recover its original functionality in the undamaged configuration in the shortest possible time is an important aspect and of great interest to the scientific community. This positive property is related to the concept of structural resilience that has been defined as “the ability of a system to reduce the chances of a shock, to absorb such a shock if it occurs, and to recover quickly after the shock” (Bruneau et al. 2003).

Researchers at MCEER (Multidisciplinary Center of Earthquake Engineering to Extreme Event) have identified four important factors that contribute to resilience as robustness, resourcefulness, redundancy, and speed. These factors have also been referred to as the four dimensions of resilience (Bruneau et al. 2003; Bruneau and Reinhorn 2006, 2007):

- (1) **Robustness:** the characteristics of a structure, or one of its elements, to withstand a given level of stress or demand (e.g. damage) maintaining its characteristic level of functionality. It can also be thought of as the concept of damage tolerance;
- (2) **Redundancy**, e.g., of load-bearing elements: the ability to develop alternative load-supporting pathways once degradation of the main elements occurs (i.e., original elements that are substitutable);
- (3) **Resourcefulness:** the ability to identify issues, set priorities, and gather resources when circumstances threaten to upset the structure or one of its elements (apply monetary, physical, technological, informational and human resources in the process of recovery to meet established priorities and achieve goals);
- (4) **Rapidity:** the ability to prioritize tasks and complete tasks quickly to limit losses, restore functionality, and prevent further interruption.

A review of the scientific literature shows that many studies aimed at the structural resilience of buildings. In this way, Cimellaro et al. (2010) pointed out a framework for evaluation of health care facilities subjected to earthquake. In this work, the evaluation of

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disaster resilience is based on dimensionless analytical functions related to the variation of functionality during a period of interest, taking into account the losses in disaster and the recovery path. Structural resilience has also been developed in different directions, where, for example, in Domaneschi and Martinelli (2016) the concept of *Immediate Resilience* is introduced as associated with the automatic function of specific elements to compensate for local out-of-services.

1.2.1.3 Bibliographic and bibliometric analysis

State-of-Art papers on the recent developments of monitoring techniques can be found in the literature (Salar et al. (2022), Yuan (2016)) but none of these faced specifically the relationship between SHM and resilience topics. The authors believe that understanding of how SHM techniques can be useful to provide information regarding Structural Resilience will play a crucial role in the future years.

To this end, bibliometric analysis has been conducted to organize available publications based on the mentioned-above relationship. This analysis was performed by achieving two main purposes:

- Provide a comprehensive State-of-Art;
- Identify and organize links between main research topics related to this field and/or connections between the most active authors.

In this study, the relevant works of literature were collected by adopting Elsevier's abstract and citation database *Scopus*. Because of the specificity of the topic, conference papers and book chapters have been included too. In the first step, a total of 97 scientific documents by searching keywords such as "*Structural Health Monitoring*" and "*Resilience*" within the *title, abstract and authors* components of each paper is found.

The total number of papers dropped to 40 once scientific contributions belonged to only the "*Structural Engineering*" subject area is selected. At this stage, the database was populated by 40 scientific articles published between 2007 to 2021, belonged to 33 different indexed

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scientific journals and written by 136 authors. Once the database was completely defined, a bibliometric analysis was conducted and graphical outcomes was obtained by using the bibliometric R-package (Aria and Cuccurullo 2017). In Figure 1.1 the total number of publications per year has been shown. The trend reveals that the highest annual growth rate occurred between 2015 and 2019. A descendent trend is recognized between 2019 to 2021 where the peak of the curve passed from 10 articles to about 7.5 articles per year, and currently (September 2022) to about 2.

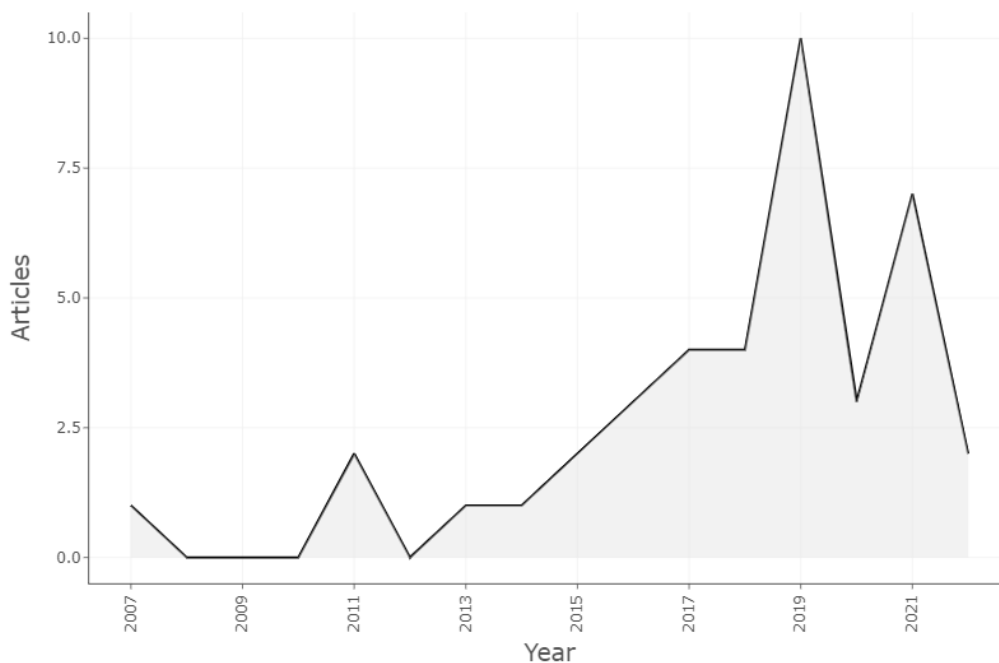


Figure 1.1: Total number of publications obtained by reviewing 40 papers.

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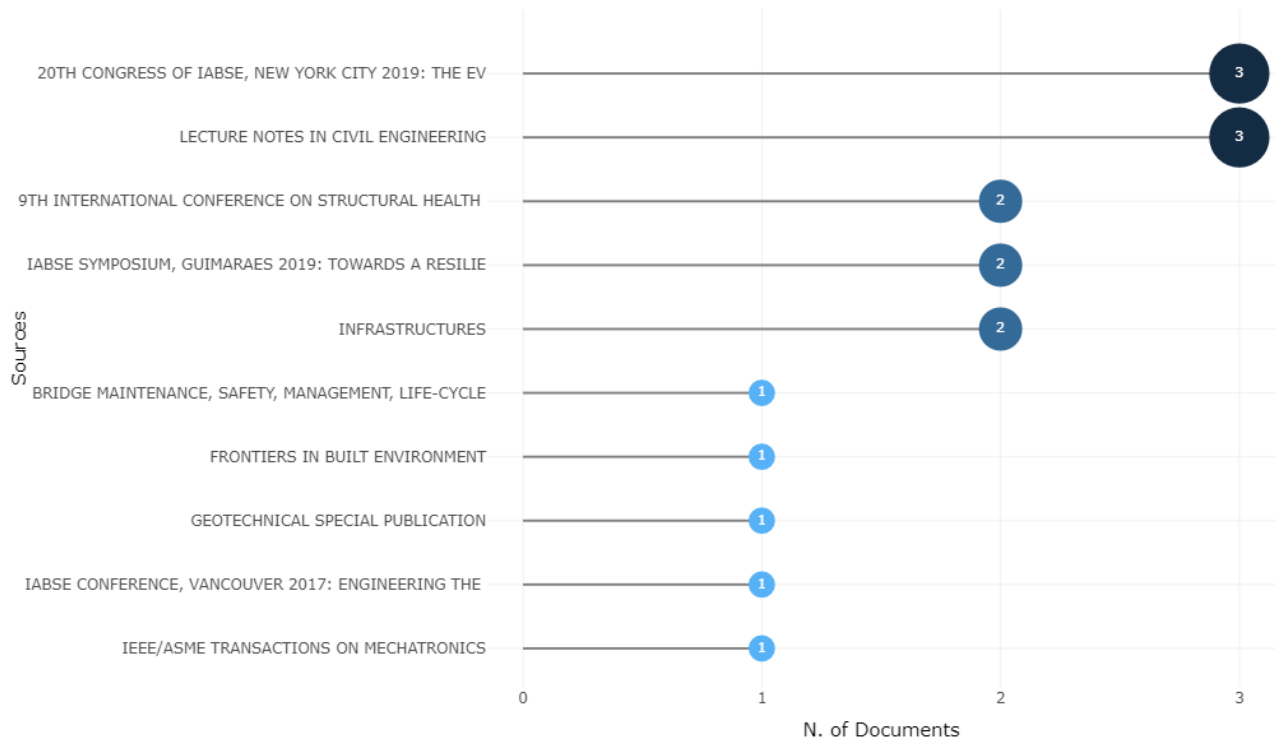


Figure 1.2: The most relevant sources carried out from the Bibliometric analysis.

The statistics of publication per journal are also provided in Figure 1.2, where the most relevant sources have been shown and the first 10 journals have been plotted.

Aiming to analyze the trend of the keyword in recent years, VOSviewer software was adopted for a graphical representation of the data. It is a software tool for constructing and visualizing bibliometric networks. Figure 1.3 depicts network visualization co-occurrence analysis, while, in Figure 1.4 an *Overlay visualization* is shown with the trend of the keyword in recent years. Maps created, visualized and explored using VOSviewer include *items that are* the author's keywords.

In the network visualization (see Figure 1.3), items are represented by their label and by default by a circle. The size of the label and the circle of an item is determined by the *weight* of the *item*. The higher the *weight* of an *item*, the larger the label and the circle of the *item* itself. Moreover, between any pair of *items*, there can be only one *link*. A *link* is a connection or a relation between *items*. In this case, the interest is focused to detect the keywords which occur together in the reviewed documents and, hence, finding the research topics which have a sort

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of relationship one each other.

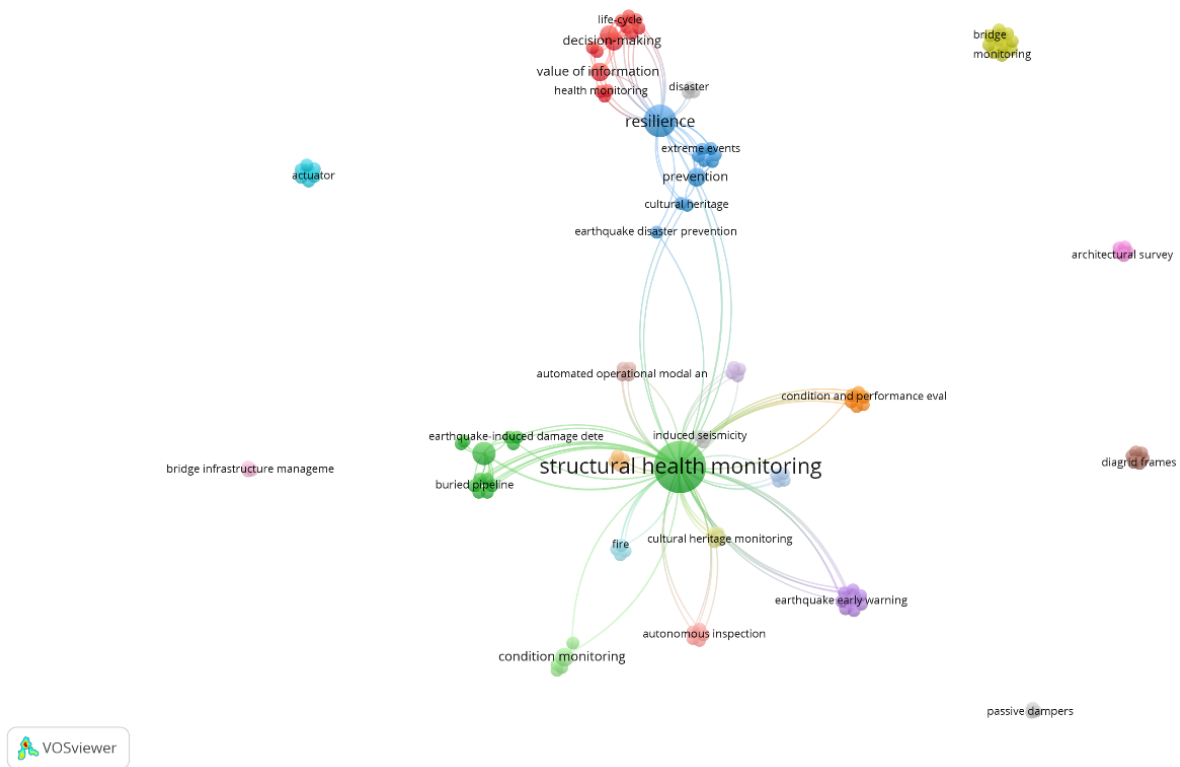


Figure 1.3: Network visualization of the co-occurrence author's keywords.

Each *link* is characterized by *strength*, represented by a positive numerical value which varies in a range between 0 (minimum strength) to 1 (maximum strength). The higher this value, the stronger the *link*.

Moreover, if the *link* attribute indicates the number of *links* to an *item* with other *items*; the *Total strength attribute* indicates the total *strength* of the *links* of an item with other items. Hence, a network is a set of *items* together with the *links* between the *items*.

A set of *items* can be grouped into *clusters*. *clusters* are non-overlapping in VOSviewer. In other words, an *item* may belong to only one *cluster*. *Clusters* are represented by colours, hence, the *items* having the same colour belong to the same *cluster*. The distance between two *items* in the visualization approximately indicates the relatedness of the journals in terms of co-citation *links*. In general, the closer two *items* are located to each other, the stronger their relatedness.

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As could be expected, in the *network visualization* depicted in Figure 1.3, it is quite evident that among the 131 keywords contained within the overall reviewed documents “Structural Health Monitoring”, “Resilience” and “value of information” are the most common. The *strength* and the *total link* which connect these three main keywords with the other ones not only are the thickest but also the most numerous. In this way, it is proved that the most significant keywords, pointed out by the bibliometric analysis, exhibit the most robust connections with the other secondary branches of the same research field. Therefore, the link between “*Structural Health Monitoring*” and “*Resilience*” passes through intermediate keywords such as “*Earthquake disaster prevention*”, “*Cultural heritage*” and “*Extreme events*”. This means that, actually, these keywords don’t appear as the only keywords in the same document but are always in conjunction with other keywords.

Moreover, other secondary topics are depicted as “*Bridge monitoring*”, and “*Bridge infrastructures management*”. These don’t exhibit any type of connection with both “*Structural Health Monitoring*” and “*Resilience*” and the distance, in terms of research topic, between the former and the latter is emphasized by the graphical distance between the *items* of each *cluster*.

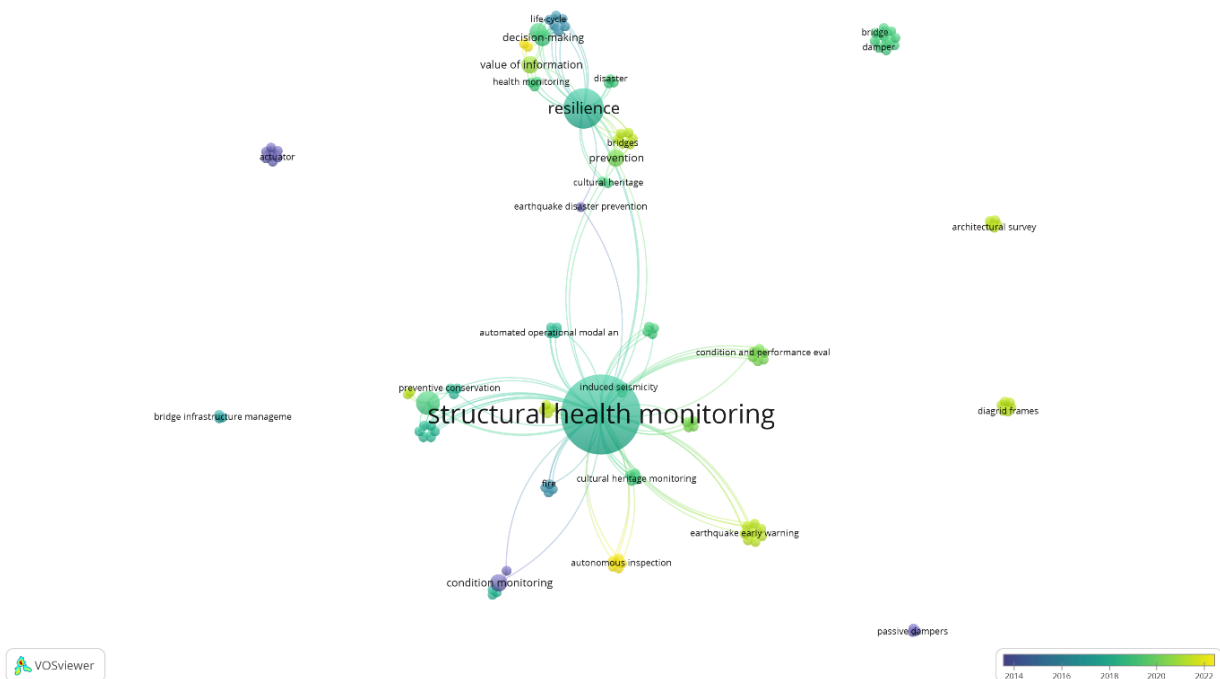


Figure 1.4: Overlay visualization of the co-occurrence author’s keywords in the last years.

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In figure 1.4, a so-called *Overlay visualization* is shown. The *Overlay visualization* is identical to the *network visualization* except that *items* are coloured differently. The colour of an item is assigned depending on the *scores* of the *item*. The *score*, adopted in this analysis, corresponds to the year of the appearance of each *item* (keywords).

It becomes clear how the most used keywords as “*Structural Health Monitoring*”, “*Resilience*” and “*Value of information*” belong to documents which were published between 2016 and 2020. It proves that the mentioned-above topics received great attention from the scientific community and its growth took place in a few years.

Another interesting map representation of the data involved in the analysis is reported in Figure 1.5, where the network of the 136 authors among collaborating researchers is shown. At the centre of the figure are placed all the authors who are the most active in this field. Each item in the network displays an author/co-author, and the link between items illustrates the co-occurrence of the knowledge channels.

It is rather evident that there is not a connected collaborating scientific community interested in some topics. Conversely, several independent groups can be seen, composed of 3 or 4 authors, which have no links with others research groups.

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overcome a disturbance with the minimum total loss of functionality in time”. Therefore, the authors described possible prospects of structural resilience based on SHM aiming at three different decision situations: before, during and after the disturbance.

Other authors (e.g., Cimellaro and Kammouh 2021; Freddi et al. 2021) presented new dynamic data-driven frameworks for effectively selecting and executing SHM systems in critical infrastructures. The introduced framework was developed to help decision-makers and infrastructure operators with the efficient use of resources for SHM, for the prediction of the best rehabilitation strategies or the refining of the risk assessment and infrastructure prioritization plan.

Achieving more inclusive resilient infrastructure frameworks represented a priority for many researchers as Achillopoulou et al. (2021). They developed resilient strategic monitoring for the estimation of the risk level of assets with no disruption to traffic in reinforced concrete bridges. Haria K. (2019) et al. proposed an innovative approach that employs satellite measurements of displacement with a 3D Building Information Model (BIM). On the same topic, Zhang Y. et al. (2019) assessed bridge resilience considering the combined effect of reinforcement corrosion and foundation sour under extreme loading using SHM techniques. Concerning the bridge application field, Ngamkhanong C. et al. (2018) realized a State-of-Art review of Railway Track Resilience monitoring in which the most promising SHM strategies have been collected.

The influence of the SHM on Resilience was also treated by Celebi M. (2015) and Asadi E. et al. (2021) concerning different San Francisco tall buildings and health monitoring for seismic Resilience quantification and safety evaluation, respectively. Few authors as Aloisio et al. faced the problem of the pinching in reinforced concrete and timber structures for the prediction of structural resilience.

However, through the critical survey conducted among all the contributions concerning

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the treated research field, a clear theoretical or analytical relation between Resilience and the four levels of SHM has not yet been achieved.

If *Damage Detection* as the first level of the SHM is considered, the provided information is the presence or not of structural damage. Any information regarding the position or the intensity of the damage cannot be provided. In this case, the damaged state of the structure is strictly related to the redundancy dimension of the same structure. Indeed, a redundant structure, independent of the type of damage, results to be safer than an isostatic (statically determinate) one. In Italy, the tragic event of the Polcevera's Bridge proves that the problem of the corrosion of the steel strands inside the concrete stays reasonably represented the main cause of the failure because of the intrinsic lack of redundancy of the structure (Morgese et al. 2020, Domaneschi et al. 2021). For this reason, the simplest information on the presence of pathologies in the structures through SHM strategies could be correlated to the grade of redundancy of the structure, to take the necessary countermeasures, such as emergency measures (e.g. evacuation, traffic reduction, shutting of critical facilities).

The second level of SHM, *Damage Localization*, can be linked to the Rapidity dimension of resilience. Once the pathology is detected and the local or diffuse damage is localized, the rapidity of the intervention and the recovery phases plays a crucial role. In this context, the SHM system may support decision-making aimed to accelerate the interventions following a priority plan, and efficiently managing the emergency. At first, the elements of the structure are affected by the damage with the main structural functions, and then secondary elements, to guarantee the minimum total cost of functionality in time.

A relationship between the Resourcefulness dimension and the third level of the *Damage Intensity* can be also identified. Indeed, the information about the damage intensity subsequent to the disturbances effectively supports the organizational and recovery phases, allowing the accurate estimation of the necessary economic and social resources to be made

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available.

Finally, the fourth level of SHM, *Prognosis*, is linked to the Robustness dimension of resilience. It is focused on the estimation of the structure's remaining life given the assessment of its current conditions. This SHM level gives, indirectly, a measure of structural robustness providing the attempt to forecast the structural performance to tolerate a specific amount of damage while retaining its usual degree of functionality.

Figure 1.6 summarizes through a graphical scheme the links between structural resilience dimensions and the four SHM phases. In the circle representation, at each slice corresponds a direct link between the selected resilience dimension and the related damage level (e.g. Damage detection with Redundancy, Damage localization with rapidity, etc.). A clockwise sense is a key to understanding the graphical representation: the external circle describes the increasing intensity level of the Damage investigation, instead the internal one shows the appropriate level of resilience knowledge that can be derived from that specific monitoring activities.

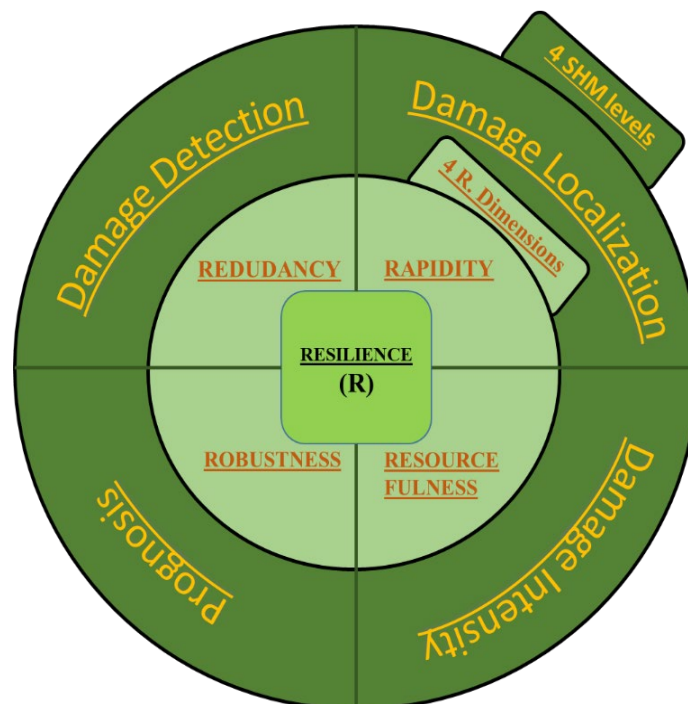


Figure 1.6: Graphical scheme of conceptual relation between SHM and Resilience.

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1.2.3 Conclusions

The subject of this chapter is the study of the connection between Structural Health Monitoring and Resilience, from their characterizations in components and phases. Subsequently, a bibliographic and bibliometric study of the state-of-the-art of their interaction was conducted to highlight the conceptual and practical links in the existing literature. It was observed how: (i) such research topics have attracted the interest of researchers, specifically in recent years, highlighting how they are topical issues; (ii) concerning the keywords of the contributions analysed, the main ones (i.e., Resilience and SHM) are often connected to intermediate keywords related to infrastructure, its management and safety, and the value of information; (iii) although there are a good number of research groups active on these topics, (iv) the connections between these groups is very low, highlighting a scenario in which there are many active but essentially independent groups in which (v) interactions are active only between members of the same individual group.

It is therefore possible to conclude from the state-of-the-art analysis that the issue of possible benefits to Structural Resilience brought by monitoring is emerging but is still in an embryonic state. So, the second part of this paper focuses on determining the conceptual relationships between the four dimensions of Structural Resilience and the four phases of the discipline of Structural Health Monitoring. It looked at the direct links by which the different phases of Structural Health Monitoring can determine, influence and improve the dimensions of Structural Resilience, and thus Resilience itself.

This purely conceptual dissertation is intended to represent a proposal that can also be a cornerstone for fostering and determining further conceptual and application developments.

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