Research on structural robustness through large-scale testing

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ABSTRACT: As a result of the persistent occurrence and apparently increasing frequency of catastrophic structural failures, recent years have been marked by a growing body of literature on progressive collapse and structural robustness. At present, the vast majority of these studies focus on computational simulations and laboratory testing of reduced-scale sub-assemblages. Although many vital aspects of structural behaviour under extreme conditions have been uncovered through such research, these strategies are characterised by significant limitations which can only be overcome through full-scale testing of real structures. This article presents some of the major research works performed in this regard by the *Building Resilient* research group from the *ICITECH* institute of the *Universitat Politècnica de València*. The most important works related to temporary shoring of buildings, cast-in-place and precast reinforced concrete building structures, steel truss bridges, and fuse-segmented buildings are presented together with the most significant results achieved so far.

1 INTRODUCTION

In recent years, several structural failures leading to catastrophic consequences for society have occurred. With respect to bridges, some of the most impactful recent examples of such failures include the collapse of the Genoa Bridge in 2017, of the Nanfang'ao Bridge in Taiwan in 2019, of the Mexico City underground viaduct in 2021, and of the Fern Hollow Bridge in Pittsburgh in 2022. With respect to buildings, it is worth mentioning that several significant structural collapses occurred in 2021, including that of the Champlain Towers in Miami, of the Siji Kaiyuan Hotel in Jiangsu, and of the residential building in Peniscola. Many of these collapses can be classified as a **progressive collapse**, which is defined as the phenomenon through which an initial localised failure propagates to other parts of a structural system, causing the collapse of the entire structure or of a disproportionate part of it.

These recent collapses can undoubtedly contribute to the erroneous perception among members of society that our infrastructure and buildings are not safe. However, although it is evident that there have been a significant number of building and bridge collapses in recent years, this does not mean that such structures are unsafe in general, or that their design is inadequate.

At present, buildings and bridges are increasingly more exposed to the devastating consequences of extreme events caused by climate change, terrorist threats, their own ageing, or inadequate maintenance and upkeep. Such events include, for example: floods, landslides, gas explosions, vehicle impacts, hurricanes, major earthquakes, terrorist attacks, etc. In addition, many of these structures are reaching the end of the useful life for which they were designed, and in many cases are frequently exposed to loads that exceed those envisaged when they were conceived.

This article presents the research currently being carried out at the *Building Resilient* research group from the *ICITECH* institute of the *Universitat Politècnica de València*. The aim of this research is to contribute to improving the resilience of buildings and bridges, by avoiding possible collapses or, at least, by minimising their consequences. The research being carried out relies on ambitious experimental campaigns involving tests on full-scale structures. Specifically, the following areas of work are presented in this article:

1) Temporary shoring of buildings
2) Flat-slab reinforced concrete (RC) building structures
3) Precast RC building structures
4) Steel truss bridges
5) Development of a new design philosophy based on connecting building segments with structural fuses

All the tests carried out involve studying how a localised initial failure can propagate to the rest of the structure. The knowledge acquired as a result of this research is allowing: 1) the definition of design and construction strategies to achieve resilient structures; 2) the definition of preventive and remedial actions for reducing the vulnerability of buildings and bridges to extreme events; and 3) the proposal of monitoring guidelines for the early detection of local failures with a high potential for causing progressive collapse.

2 PROGRESSIVE COLLAPSE

A progressive collapse occurs when an initial failure, in one part of a structure, sets in motion a chain of failures leading to the collapse of the whole structure or of a disproportionate part of it. This type of collapse is usually associated with severe loss of life and property. Some of the best-known cases of progressive collapse in building structures include Ronan Point (London, 1969), Capitán Arenas (Barcelona, 1972), U.S. Marine Barracks (Beirut, 1983), the Asociación Argentina Israelita (Buenos Aires, 1994), and the A.P. Murrah Federal Building (Oklahoma, 1995). More recent cases of progressive collapse include the collapse of the Champlain Towers in Miami and that of a residential building in Peniscola, both occurring in 2021.

For the case of bridges, a classic example of progressive collapse is the Quebec Bridge, which collapsed during construction in 1907 due to the buckling of steel bars. More recent examples of progressive collapse include the I-35W bridge in Minneapolis, which completely collapsed in 2007 due to the failure of a single gusset plate, or the Chauras bridge in India, which collapsed in 2012 due to the erroneous design of a few steel bars.

Considering the importance of avoiding progressive collapse, current design codes have introduced the concept of **robustness**, understood as insensitivity to initial local damage. Making societies resilient requires resilient infrastructure. For this reason, there is a clear need at the present time for robust buildings and bridges, in which localised initial failures caused by abnormal events do not propagate. This need is made evident by the continuous updating of current structural design standards and the growth in the number of scientific publications related to structural robustness (Adam et al. 2018, El-Tawil et al. 2014).

A robust structure must be able to activate alternative load paths after a localised initial failure. In this way, the load previously supported by the failed element can be redistributed to the rest of the structure. This ability to activate alternative load paths is usually achieved by providing structures with continuity, redundancy and ductility.

3 STRUCTURAL ROBUSTNESS RESEARCH

The work of the *Building Resilient* research group is carried out within the framework of the *ICITECH* institute of the *Universitat Politècnica de València* and aims to contribute to improving the resilience of buildings and bridges. To achieve this goal, the group conducts research in two fields: 1) structural assessment, including structural monitoring and risk analysis; and 2) progressive collapse and robustness of structures. Traditionally, research in the field of robustness and progressive collapse of structures has focused mainly on computational simulations and laboratory tests on reduced-scale specimens, typically sub-assemblages of a structural system. The research being carried out at *Building Resilient* seeks to go further by employing experiments on full-scale structures for the study of robustness and progressive collapse. In the following subsections, a brief description is given of five of the group's current research projects in the field of robustness and progressive collapse.

3.1 *Temporary shoring*

Considering the consequences of failures during the construction of buildings (Buitrago et al. 2018a, Carper 1987, Hadipriono & Wang 1987), the *Building Resilient* group opened a new line of research related to the robustness and progressive collapse of buildings under construction. This research was funded by the *Ministerio de Educación y Formación Profesional* and the *Generalitat Valenciana*. The research was pioneering worldwide, as it was the first study analysing how the failure of one or several elements of a temporary shoring system can lead to the progressive collapse of the entire shoring system (Fig. 1), or even of the entire building under construction.

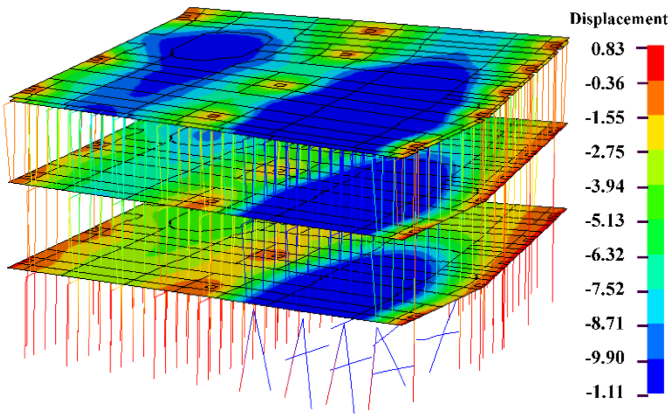

Figure 1. Computational simulation of failure propagation in a temporary shoring system.

This research allowed the identification of the alternative load paths that can be activated in the event of the failure of one or more elements of a shoring system (Buitrago et al. 2018b).

One of the most innovative and impactful outcomes of this research relates to the design of a novel structural fuse, which is placed in the prop as shown in Figure 2. This device has been patented and represents the first example of a structural fuse specifically intended for preventing the progressive collapse of structures.

Figure 2. Structural fuse used to limit the maximum load a prop can bear.

As demonstrated through an ambitious experimental campaign (Fig. 3) and through computational simulations (Buitrago et al. 2021a), use of the structural fuse improves the robustness of shoring systems and can therefore prevent the propagation of local failures in buildings under construction (Buitrago et al. 2020a).

Figure 3. Construction of test building for validating the performance of structural fuses.

3.2 *Flat-slab RC building structures*

Thanks to funding received from the *BBVA Foundation* through a *Leonardo* Grant, the *Building Resilient* group was able to carry out a research project in which a full-scale test building was subjected to different corner-column failure scenarios (Fig. 4). In fact, corner columns of a building are precisely the ones that are most exposed to extreme events, such as those due to terrorist attacks, vehicle impacts, or extreme environmental actions. Additionally, when a corner column fails, there are typically less alternative load paths available for load redistribution.

Figure 4. Test building prepared for sudden column removal.

This research has allowed the analysis and evaluation of possible alternative load paths that can be activated after the failure of corner columns, taking into account the dynamic effects caused by the sudden removal of the column (Adam et al. 2020, Garzón-Roca et al. 2021). Considering the magnitude of the tests, this is one of the most ambitious projects carried out to date in the field of robustness and progressive collapse of buildings. The experimental campaign also included a test scenario with masonry infill walls (Fig. 5) to study how these elements contribute to activating alternative load paths (Buitrago et al. 2021b).

The work currently being performed is now focusing on advanced computational simulations (Buitrago et al. 2020b) in order to extrapolate the experimental results to different scenarios from those tested.

Figure 5. Test building for analysing the contribution of masonry infill walls.

3.3 *Precast RC building structures*

Precast RC elements are most definitely gaining importance in the field of building construction. The special characteristics of these constructions, especially in terms of the joints between elements, make them, a priori, more vulnerable when exposed to extreme events. With the *PREBUST* project, funded by the *Ministerio de Ciencia e Innovación*, *Building Resilient* seeks to improve the robustness of building structures made with precast RC components.

The most ambitious part of *PREBUST* is the experimental campaign involving a full-scale test building, built specifically for this project. The building is two storeys high and has a floor plan of 15×12 m^2. The building is being subjected to three different sudden column removal scenarios. Preliminary results already indicate that, with appropriate construction details, precast RC structures can exhibit sufficient robustness to prevent the propagation of local-initial failures (Makoond et al. 2021). Thus, it is possible to construct buildings with precast RC components that are safe in extreme situations (Fig. 6).

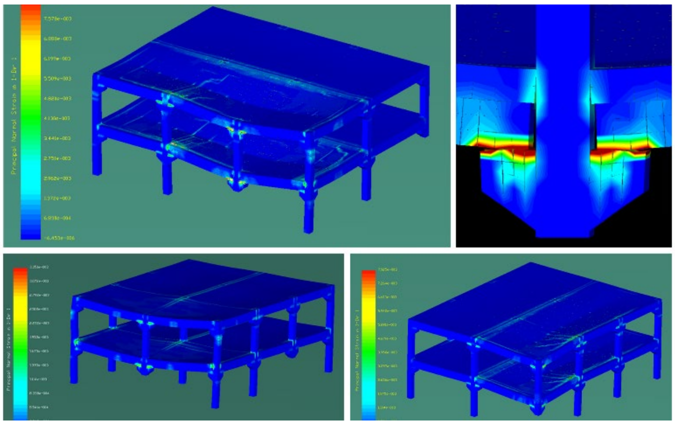

Figure 6. Computational simulations of the response of a precast concrete structure for various column failure scenarios.

3.4 *Steel truss bridges*

Steel truss bridges are particularly sensitive to progressive collapse. This means that a local failure can propagate to the rest of the bridge, resulting in catastrophic consequences. In collaboration with the *Calsens* spin-off company, *Building Resilient* is investigating how alternative load paths are activated after local-initial failures in this typology of bridges. To this end, funding has been received from *FGV* (*Ferrocarrils de la Generalitat Valenciana*) and the joint venture formed by the companies *FCC*, *Convensa* and *CHM*. Funding is also being received from the *Ministerio de Ciencia e Innovación*.

The work carried out has included the laboratory testing of a 21 m long railway bridge span (Fig. 7). The tests involved the removal of a number of bars in order to assess the possible resulting failure propagation (Buitrago et al. 2021c). This experimental campaign has allowed the robustness of the bridge to be evaluated and monitoring guidelines to be defined for the early detection of potential local failures that can propagate. It has also permitted the development of fault trees that can be employed to evaluate the safety of historic steel bridges (Sangiorgio et al. 2022).

Figure 7. Complete span of a railway bridge inside the ICITECH laboratories.

The work now being performed focuses on computational simulations involving the analysis of different failure scenarios and their possible propagation to the rest of the bridge (Fig. 8).

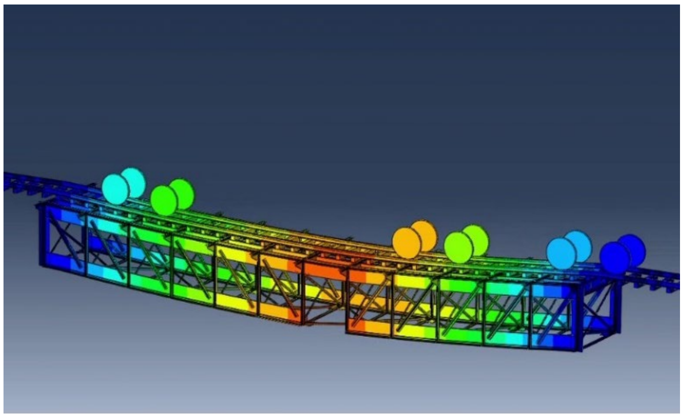

Figure 8. Computational simulation of a local failure in a steel truss bridge.

The acquired knowledge through this research is currently being applied to the upkeep of three in-service railway bridges, which are extensively monitored and provide key information for structural assessment in real-time, 24 hours a day (Adam et al. 2021).

3.5 *Endure Project*

Current building design codes are based on providing structures with a high degree of continuity. Thus, when one element fails, the load it supported can be redistributed among the other elements of the structure. Although this design philosophy has been effective on many occasions, there are certain scenarios in which it is not, and can in fact even increase the risk of progressive collapse (Adam et al. 2019). Therefore, it is necessary to define new design approaches to remedy these limitations in order to mitigate the risk of disaster.

The aim of the *Endure* project is to develop a new building design philosophy based on fuse segmentation to prevent failure propagation. This new philosophy aims to protect buildings against progressive collapse by connecting different segments of a building with structural fuses. These fuses will give continuity to the structure for scenarios considered by current design codes but will separate the segments when failure propagation is inevitable during exceptional scenarios for which design codes are not effective. This project, funded by the *European Research Council* with 2.5 million euros, will involve: 1) the theoretical development of the new design philosophy, 2) the design and manufacturing of fuses, and 3) the implementation and validation of the new design philosophy in two real buildings (Fig. 9).

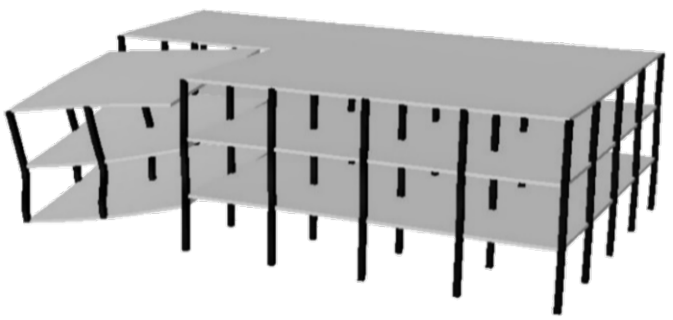

Figure 8. Schematic of a building to be tested as part of Endure.

4 CONCLUSIONS

Achieving resilient infrastructures and buildings that can recover from extreme or abnormal situations is an important societal challenge of present times. Extreme situations often cause initial local damage to critical elements of buildings and bridges, which can lead to progressive collapse. Since resilient infrastructure is needed for building a resilient society, a key aspect towards achieving this goal lies in preventing the occurrence of progressive collapse.

This article described the work being carried out at the *ICITECH* institute of the *Universitat Politècnica de València* in the research area of progressive collapse and robustness of buildings and bridges. This work is bearing fruit by achieving a better understanding of the alternative load paths that are activated by local-initial failures in buildings and bridges. Research outcomes are allowing the development of: 1) devices that prevent the propagation of failures in temporary shoring systems; 2) simplified guidelines for the robust design of cast-in-place reinforced concrete (RC) buildings; 3) construction details for robust buildings built with precast RC components; 4) monitoring guidelines for early detection of the potential propagation of local failures in steel truss bridges; 5) a new structural design philosophy addressing the limitations of current building codes.

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