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A Framework for Improving Building Robustness Through Segmentation

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Abstract. The protection of buildings and infrastructures from extreme abnormal events due to natural hazards (e.g. hurricanes, floods), accidents (e.g. vehicle impact, gas explosions, unexpected failure due to poor design or lack of maintenance) and malicious actions (e.g. terrorist attacks), is currently of great societal and scientific concern. To prevent the spreading of a local-initial damage into progressive collapse, the current design philosophies consider that when a critical element fails (e.g. column, load-bearing wall), continuity structural details should provide alternative load paths to redistribute the load of the failed element to the rest of the structure. Although this strategy is valid in certain situations (e.g. small initial failure), in others (e.g. large initial failure due to blast loading), it has proved to be mistaken and has led to disastrous consequences. Over recent years, a debate has emerged about whether or not segmentation can improve a building's capacity to arrest progressive collapse. Segmenting a building into individual parts can prevent failures in one zone from propagating to other parts of the structure, as was the case, for example, in the Pentagon (2001) and Terminal 3 of the Charles de Gaulle Airport (2004). However, segmentation breaks continuity, which works well for small initial failure scenarios. In the context of an ERC-Consolidator Grant project, the use of structural fuses has been proposed. While fuses will provide continuity under normal loads or for small local-initial failures currently considered by relevant standards, they will separate to prevent disproportionate collapse during more extreme situations when failure propagation is inevitable. This paper presents the first achievements of the project, involving the development of a framework that can be employed to identify situations when continuity is disadvantageous and for which segmentation is beneficial.

1 Introduction

The safety of buildings and infrastructures from extreme events due to natural hazards (e.g. hurricanes, tsunamis, floods), accidents (e.g. vehicle impact, gas explosions, unexpected failure due to poor design or lack of maintenance), and malicious actions (e.g. terrorist attacks) is currently of significant societal (and scientific) concern.

Achieving resilient societies involves making the buildings and infrastructures we use resilient, i.e. making them able to withstand and recover from abnormal situations such as extreme events, which often cause local damage in building structures that can spread to the rest of the building in the form of a "progressive collapse" [1]. Present

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building designs to prevent progressive collapse are based on the "robustness" concept, which allows severe local damage to occur after an extreme event but prevents it from propagating to the rest of the structure [2].

The aim of current design philosophies is that when an element fails (e.g. column, load-bearing wall), alternative load paths (ALP) should exist to redistribute its load to the rest of the structure. Although this strategy has been shown to be valid in certain situations [3–7], in others, it has proved to be mistaken and has led to disastrous consequences [8]. Providing a building with extensive continuity (or ties) certainly does activate ALPs. Still, after the failure of, e.g. a column, there are other situations in which the ties can help to propagate a local failure and lead to total collapse [9].

Segmenting buildings has recently been proposed to avoid progressive collapse. In certain situations, segmentation avoids a local failure propagating to the rest of the building, as happened, for example, in the Pentagon (Washington 2001) and Terminal 3 at the Charles de Gaulle airport (Paris 2004). Although neither case segmentation had been included in the design to avoid progressive collapse, it proved to be highly efficient at controlling local failures. Segmentation by expansion joints could be counter-productive by breaking continuity, which is necessary under diverse types of load. Some authors [8, 10] have suggested using fuses to join different structural segments. These would provide continuity under normal loads, while they would separate the different parts of the building under extreme loads involved in extreme events with the possibility of progressive collapse, allowing part of the building to collapse in order to preserve the rest in situations in which total collapse is inevitable. Despite the possible advantages of this system, it has not been used so far to improve robustness and avoid progressive collapse. Fuse segmentation is probably the only alternative to make up for the present codes and recommendations gaps.

This approach is the overall aim of Endure, a Consolidator Grant funded by the ERC with €2.5million, which aims to develop a novel fuse-based segmentation design approach to limit or arrest the propagation of failures in building structures subjected to extreme events. The main aim of this conference paper is to define a preliminary framework for the Endure project to establish the basis of working during the project's lifetime.

After this introduction section, the paper is organised as follows. Section 2 describes the advantages and limitations of continuity and segmentation, whereas Sect. 3 describes the new approach by using structural fuses to take advantage of both continuity and segmentation at the same time. Section 4 describes the preliminary framework, and Sect. 5 draws the paper's main conclusions.

2 Continuity and Segmentation. Advantages and Limitations

The current codes (e.g. Eurocode 1, part 7 [11]), guidelines and recommendations (e.g. DoD or GSA [12, 13]) and the scientific community [6] agree that progressive building collapse can be avoided in three ways: 1) by defining continuity reinforcement in the form of ties (horizontal and vertical); 2) by defining Alternative Load Paths (ALP) so that the loads supported by the failed load-bearing elements can be transferred to neighbouring elements; and 3) by designing a series of key elements able to resist an extreme event and avoid the appearance of local failures.

Currently, the current codes and recommendations give special attention to the steps to activate the ALPs after a column failure in a building. It is considered that a robust structure should be able to activate the ALPs that will allow the loads on the failed elements to be redistributed to other elements in the structure. The main mechanisms that can be used to provide ALP and minimise the risk of progressive collapse are: a) Vierendeel beam behaviour of the frame over the failed column (Fig. 1a), b) catenary-membrane action of beams-slabs, bridging the damaged column (Fig. 1b), and c) the contribution of non-structural elements (Fig. 1c). Effective ALPs can be achieved by giving a structure continuity, redundancy and ductility [14–16].

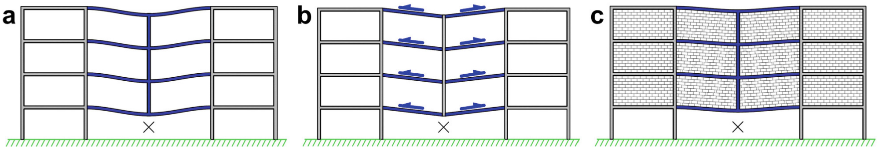

Fig. 1. Alternative load paths: a) Vierendeel action, b) catenary action, and c) contribution of non-structural elements.

Designs based on current approaches have proved to be effective on various occasions. The Khobar Towers were an example of a specific design for continuity, redundancy and ductility that avoided progressive collapse, despite the severe damage the building had suffered after a terrorist attack. However, in certain situations, continuity produces undesirable effects. It increases the risk of progressive collapse, as happened in the failures of the Viadotto Cannavino Bridge and the Haeng-Ju Grand Bridge. Both bridges collapsed under construction after one of their spans failed. As continuous prestressing cables were used, when the span failed, it pulled ten or more contiguous spans after it. Looking at rack failures in warehouses (a very common event due to rapid construction and poor operation), one can also clearly understand that continuity is not always a good choice for structural robustness. This situation, where continuity, redundancy and ductility have undesirable effects on structural integrity, can also occur in buildings (Murrah Federal Building in Oklahoma, 1995). In this context, if one part of a building fails, it may cause the collapse of the neighbouring parts or even the entire structure. Thus, the risk of progressive collapse may be increased when slabs and beams are firmly tied together. In these situations, continuity means that it pulls on the other zones and causes further collapses.

Given the above-mentioned problems, there is a need to explore and define new tools and methods that will help to overcome the limitations of the present design philosophies to obtain robust buildings. In this direction, there have been many situations in which a local failure caused by an extreme event has not spread to other parts of the building thanks to its being segmented; i.e. since the structure is divided into separate parts with no intervening continuity, the failure or collapse of one zone has no effect on the others.

Some examples of this include: 1) the Pipers Row car park (Wolverhampton, 1997; Fig. 2a), where the punching shear failure of a series of columns did not spread to the other parts of the building thanks to the discontinuous slab reinforcement; 2) when a plane hit the Pentagon (Washington, 2001), one zone of the building collapsed but the damage did not spread to the rest of the structure. The Pentagon is formed of five modules separated by expansion joints, which prevented the propagation of the initial failure; and 3) when part of a concrete roof collapsed in Terminal 3 of the Charles de Gaulle Airport (Paris, 2004; Fig. 2b), the damage was confined to the initial zone since the structure had been segmented into bays. Clearly, segmentation has been shown to be occasionally and fortuitously beneficial in containing damage during structural failures. Although it was seen to work well in many cases, it was not purposely adopted to avoid progressive collapse.

Fig. 2. Partial collapse of: a) Pipers Row car park and b) Terminal 3 of the Charles de Gaulle Airport.

Segmentation is currently used as a control measure against thermal and seismic movements in structures and has not been used so far to design robust buildings resistant to progressive collapse and has hardly been mentioned in the scientific literature [17–19]. Comparing the limitations of the present design methods against progressive collapse and the advantages offered by segmentation, an analysis of its risks and consequences should be made to clearly define the situations in which it would be beneficial, as well as how it should be implemented in buildings.

3 Structural Fuses – A New Concept

As segmenting a building by expansion joints can be effective in certain situations, the lack of continuity can be harmful in others, so some authors [10, 19] have suggested using fuses to join the different building segments. Fuses should be able to transmit the ordinary design loads and even the accidental loading proposed in the different codes. They should also be able to provide the structure with sufficient continuity to withstand the failure of a single column, as recommended in the current standards, thus preventing a progressive collapse. Fuses would go into action when an extreme event is of such a magnitude that the forces generated by a local failure would pull down the rest of the structure and propagate the collapse to other parts of the building. Fuses should therefore be defined based on the maximum loads at which brittle failure would occur to prevent the transmission of loads between segmented sections.

A fuse-based system takes advantage of the benefits of continuity to give robustness to the structure while at the same time managing to increase robustness in exceptional circumstances (e.g. failure of more than one column, one bay slab or long-span slab) by allowing one zone to fail and then confining the failure to this part only. This approach is radically different to that used in the latest studies on progressive collapse, which focus on improving ALP effectiveness by giving the structure continuity, redundancy and ductility. This fuse-based system to segment buildings would have radically different behaviour to those used in seismic engineering since their aim is not to dissipate energy but rather to disconnect under a given load and separate the rest of the segments to avoid the total collapse of the building.

4 Definition of a Preliminary Framework

To introduce fuses into building designs, it will first be necessary to define a framework for establishing: a) situations in which the use of fuses is beneficial and when they should be activated; b) possible fuse designs that may be different for different types of structures (e.g. concrete or steel structures); c) testing the possible designs so that their structural behaviour can be established and analysing which designs perform best; and d) validating the designs in actual buildings. Thus, the framework that has been established in the Endure project has been preliminarily defined as follows:

1. Performance-based approach for the design of fuse-segmented buildings, in which the selection of target buildings and the definition of the position of fuses will be defined.
2. Designing, manufacturing and testing fuses, in which several designs for different building typologies will be carried out and then manufactured and tested in isolated and substructures (see Fig. 3).

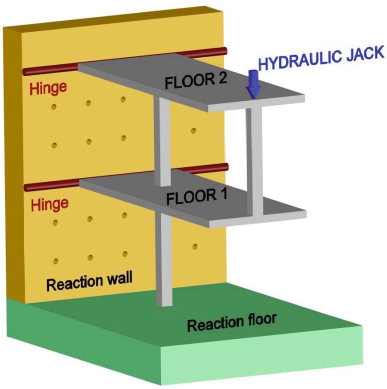

Fig. 3. Preliminary test setup in substructures.

3. Implementation and validation-testing on actual buildings, in which the final fuse designs will be implemented in real-scale buildings and tested to analyse their appropriateness in actual buildings (see Fig. 4).

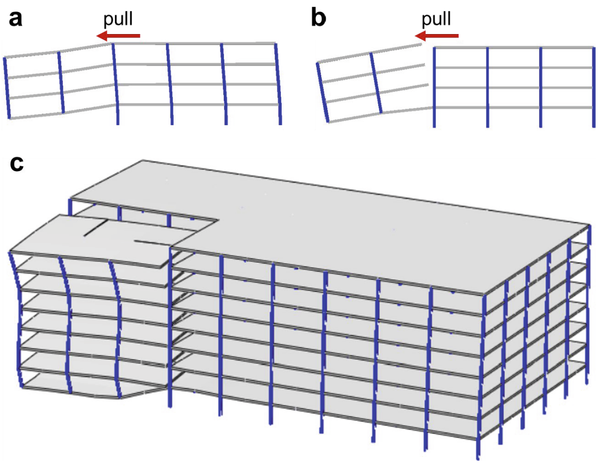

Fig. 4. Preliminary test setup for actual buildings.

5 Conclusions

This paper presents the first achievements of the Endure project, an ERC Consolidator grant which aims to develop a novel fuse-based segmentation design approach to limit or arrest the propagation of failures in building structures subjected to extreme events. One of the first achievements involved the development of a preliminary framework that can be employed to identify situations when continuity is disadvantageous and for which segmentation is beneficial. If segmentation is thus recommended, the framework also considers the definition of the structural fuse position and the following steps regarding the definition of the structural fuse designs and subsequent tests on substructures and real-scale structures.

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