Summary

The main purpose of this research was to develop a strategy for selective retrofitting against progressive collapse, using high-fidelity numerical models to reproduce collapse propagation. In other words, the purpose was to understand if it can be possible to detect any specific path in collapse propagation, and if any specific lack of structural details or structural design mistake can be selected and fixed to prevent the initial failure and its spreading to the rest of the structure.

To do so, the research investigated four well-known collapse cases occurred over the last few decades: the collapse of the Polcevera Viaduct in Genoa in 2018, the partial collapse of the Champlain Tower South residential building in Surfside, Miami, in 2021, the collapse of the Pyne Gould office building in New Zealand in 2011, and the collapse of the transept and main dome of the Basilica di Collemaggio in L'Aquila, after the 2009 seismic event. The initial work consisted of retrieving the original construction drawings of the structures. In the case of the Polcevera Viaduct and Pyne Gould Building, most of the original drawings were accessed through online resources. The original drawings of the Champlain Tower South were requested for research purposes to the municipality of Surfside, Miami. The history of the Basilica di Collemaggio was reconstructed by accessing the Office for Preservation of Cultural and Architectural Heritage archive in L'Aquila. Due to the complex geometry, some of the investigated cases also required direct data acquisition through either a terrestrial laser scanner (Basilica di Collemaggio), or trough photogrammetric point cloud generation from aerial and satellite images (Pyne Gould building and the Polcevera Viaduct).

Next, detailed AEM numerical models were developed based on the retrieved data: 3D elements (8-node cuboids) connected through implicit springs were employed to reconstruct the geometry of the buildings; reinforcing bars (RTF), in reinforced concrete (RC) assembly, were introduced by coupling the mechanical contribution of implicit springs having equivalent area. The Maekawa and Okamura

(1983) elastoplastic model was generally considered for matrix springs representing the axial behaviour of the concrete material; the Menegotto and Pinto (1973) cyclic model was employed for equivalent springs representing the reinforcing bars. The work involved the exact reproduction of the reinforcing bars, stirrups, and tendons' shape in ordinary and pre-stressed assemblies. In addition, degradation phenomena were also considered by introducing area reduction factors in specific portions of the structures. Several sensitivity analyses were carried out, considering both non-linear static (degradation stage) and dynamic analyses (collapse stage).

Among others, the time step, the number of increments, and the proper mesh ratio to reliably represent the collapse phenomenon were investigated, trying to strike a balance between analysis accuracy and the use of computational resources.

Initial analyses were carried out comparing different validation cases, from 2D-frame component level to 3D plane problems (Grunwald et al. 2018), while comparing analysis results and experimental data. Preliminary data on analysis parameters were acquired by comparing actual collapse test results, carried out at Politecnico di Torino's laboratory on an RC beam sample, to AEM analysis results using the Digital Image Correlation, DIC, technique. Results were presented at the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), held in Sapporo, Hokkaido, Japan, in 2021, and later published in 2021 in Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations edited by Taylor & Francis (Marco Domaneschi et al. 2021). Specific time steps, mesh ratios, and material parameters were defined considering both the initial crack propagation and the collapse phase when element separation and collision occur.

A thin section correction factor in the case of one-element dept in the mesh was considered in the full collapse analysis; in addition, an RTF bending ratio was also introduced to replicate the actual shear stiffnesses of bars in cracking concrete. A micro-modelling approach was adopted in the development of the numerical model of the Basilica di Collemaggio, introducing equivalent springs representative of the combined behaviour of units and mortar, while also replicating the actual stagger pattern of the original masonry.

The initial approach was a forensic one: it consisted of applying to the structures the collapse load which could have determined the observed collapse; the Pyne Gould building and the Basilica di Collemaggio, were subject to the same ground motion acceleration recorded from a nearby station the day of the collapse; the Polcevera viaduct and the Champlain Towers building, which apparently collapsed without any significant external load applied to the structure, were highly degraded till collapse occurred.

In all the cases a series of “what if” scenarios were investigated: in the case of the Polcevera viaduct, which essentially consisted of macro-elements composed in a “balanced system” (the tower, the deck, the trestle, and the strands), a series of degradation analyses were carried out considering the residual capacity of each macro-element. Analysis shows that both the deck, the trestle, and the tower itself would have been able to withstand levels of degradation that far exceeded what was reported in the report about the condition of the structure. However, the collapse of the structure was easily achieved when degrading the strands. In addition, it was observed how the loss of one of the strands would have induced a torsional force in the deck which was not considered in the original design. Finally, the derived collapse mechanism was compared with the actual footage of the collapse and found to be reasonably in accordance. A comparison between the actual debris distribution obtained by reconstructing the 3D point cloud of the area from aerial images and the actual analysis results was also discussed and the final findings of the research were published in Engineering Structures edited by Elsevier: “Collapse analysis of the Polcevera viaduct by the applied element method”, M. Domaneschi, C. Pellecchia, E. De Iuliis, G.P. Cimellaro, M. Morgese, A.A. Khalil, F. Ansari (M. Domaneschi et al. 2020). The collapse of the Champlain Towers condo in Miami was investigated by assuming both differential foundation settlement and localized degradation scenarios. During the research, it was observed how the building was sensitive to the loss of perimeter columns, due to the reduced load redistribution capacity at the perimeter of the building.

The analysis found the hypothesis of differential foundation settlement unrealistic, as it would have involved a significant number of columns with no actual evidence of such diffuse damage.

On the other hand, while testing different degradation scenarios, it was observed how the collapse of a single slab at the basement level would have initiated a disproportionate collapse of the structure. In fact, the one-floor basement was composed of high-depth beams directly connected to the perimeter columns of the twelve-story building. The deep beams were functioning as “slab drops”, covering the different elevations at the perimeter of the pertinent area of the building. Their failure, due to degradation, would have induced a significant bending moment on the perimeter columns, which were not designed to sustain it.

In addition, the resultant collapse dynamic was found to be reasonable in accordance with what was recorded by a surveillance camera on the day of the collapse. The findings of this research were published last year in the Journal of Structural Engineers edited by ASCE: “Progressive Collapse Analysis of the Champlain Towers South in Surfside, Florida”, C. Pellecchia; A. Cardoni, G. P.

Cimellaro, M. Domaneschi, F. Ansari, A.A. Khalil. In the case of the Pyne Gould Building, it was observed how the time-history record of the 6.3 Magnitude earthquake that occurred the 22 February 2011, would have induced a flexural/buckling failure in the RC core of the building. In fact, a vertical discontinuity was found in the east core wall of the building, most probably due to architectural distribution reasons. Such discontinuity would have induced a failure just above the ground floor of the building, where the core wall was missing. Additional analysis carried out employing several different time-history records showed a collapse mechanism originating always from that specific point of the structure. Analysis results were validated by comparing a 3D point cloud derived from satellite images of the actual debris distribution to the actual collapse shape resulting from the analysis. The deviation between the two models was found to be within acceptable range and the findings of the research were later published in Engineering Structures edited by ELSEVIER: "Reliability of collapse simulation - Comparing finite and applied element method at different levels", C. Grunwald, A.A. Khalil, B. Schaufelberger, E.M. Ricciardi, C. Pellecchia, E. De Iuliis, W. Riedel (Grunwald et al. 2018).

Most of the research was carried out on themes related to progressive collapse and collapse simulation; however, slightly different was the work carried out to assess the spreading of damage in the Basilica di Collemaggio, as a consequence of the 5.9 Magnitude earthquake that struck the city of L'Aquila the 6 April 2009. The Basilica di Collemaggio is one of the most known and iconic examples of architectural heritage in L'Aquila. As most of the architectural heritage, is the result of centuries of transformation and overlay of different construction techniques and peculiar structural details. The research investigated the capabilities of the AEM technique to reliably replicate the seismic behavior of the Basilica by employing a micro-modeling approach, considering the different staggered patterns in the different masonry specimens, the presence of voids, cavities in the masonry walls, as well as the actual unit distributions in vaults and columns. In addition, the presence of steel bars and RC beams was also considered and explicitly introduced in the numerical model either by means of 3D elements or implicit springs. The actual staggered pattern of masonry and the complex geometry of the Basilicas were reconstructed via terrestrial laser scanning. The point cloud was transposed into 3D elements representing the same units while equivalent springs were introduced to replicate the combined behavior of unit and mortar. The obtained numerical model was able to replicate crack patterns and in-plane/out-of-plane behavior of the Basilica. The final damage pattern obtained through non-linear dynamic analysis, employing the time-history record of a nearby station on the day of the strike, was finally compared to the actual damage observed using an ortho-photo technique. The analysis has shown an overall damage state comparable with what was observed after the earthquake and the results of the research were presented at COMPDYN 2023, 9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, "*Damage pattern analysis of the Basilica di Collemaggio using AEM micro-modeling*", C. Pellecchia, A. Cardoni, G.P. Cimellaro, A. A. Khalil (Pellecchia et al. 2023).