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ASSESSMENT OF THE EFFECTIVENESS OF CABLING SYSTEM CONFIGURATION IN RETROFITTING STEEL-CONCRETE COMPOSITE BUILDINGS

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Abstract. *Steel cables have been extensively used in structural design. Even though their most prominent use is in the design of large span cable stayed or prestressed bridges, a variety of applications in buildings has also been realized. In structural design, cables are mainly used as components of (a) prestressed concrete or post-tensioned steel beams, in order to increase their resistance in bending moment, (b) self-centering systems as a means to restore the connected element to its initial position, or (c) bracing systems as an alternative to the typical steel sections. In the past decade, the use of cables has been proposed as a means of creating ties within a structure, in order to increase its collapse resistance.*

The mechanical behavior of steel cables and its numerical modeling has been extensively investigated experimentally and numerically [1-16]. However, a concise numerical investigation of their effectiveness in retrofitting steel-concrete composite buildings using three-dimensional models has not been performed. In this work, various cable system configurations are assessed with respect to their effectiveness in retrofitting steel-concrete composite buildings. The selected buildings have been found to be deficient regarding their progressive collapse resistance. Cables are installed (a) in various bays of the building, (b) parallel to its structural elements and (c) under the composite slab in order to improve their performance. The effect of post-tensioning on the efficiency of the steel cables is also evaluated. The results yielded illustrate the effectiveness of each configuration.

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1 INTRODUCTION

In structural design against seismic loads, apart from the required ductility, structural elements need to have an adequate stiffness so that the overall fundamental period of the structure is sufficiently limited. In steel and composite buildings, this is either achieved entirely by their columns (moment resisting frames) or using bracings (braced frames). Typical bracing sections used in practice are angular sections (L-shaped) or hollow circular or rectangular sections. L-shaped sections are easier to assemble as they are bolted directly to the connection plates, but are susceptible to buckling under compression or torsion when the horizontal loads on the structure are not parallel to the bracing's longitudinal axis. The buckling resistance of hollow sections is particularly larger, but damage has often been found to concentrate on their connections increasing significantly the cost of repair. This has led researchers to propose and test novel connections that remain damage-free, as specific components yield before all others, so the damage is limited in them [17-21]. Despite their undoubted efficiency, engineers often do not take into consideration their application in conventional buildings mainly due to lack of knowledge. Steel cables are a suitable alternative, as they receive only tension, while they deform in compression or torsion without losing their properties. Hence, they do not transfer strong compressive loads to their connections which would damage them. Therefore, they are a conventional solution with simple application that could be more attractive to engineers in practice, provided that there are guidelines to support the design procedure indicating the appropriate positioning and selection of characteristics.

Progressive collapse is a topic of increased scientific interest [22-52], as it is large scale structural failure caused as a chain reaction by small scale initial damage. It is an unacceptable failure type, not only due to the disproportionate propagation of structural damage, but also because it usually takes place extremely fast, or practically instantly. Available guidelines such as UFC 4-023-03 [53-54] or the GSA guidelines [55] provide the general framework to enhance the robustness of a building in order to increase its progressive collapse resistance. Design of structures against such scenarios is not compulsory in the existing design codes, mainly because of the lack of adequate scientific literature, even though such documents are currently in preparation. Hence, buildings designed according to the latest design codes but without taking into consideration damage scenarios that might cause progressive collapse need to be retrofitted in order to minimize their progressive collapse potential.

Retrofitting a building, whether it is achieved by strengthening individual existing members, such as columns or beams, or by installing additional ones, such as bracings or cables, should be as less invasive as possible. This is required in order to reduce the total cost of the operation as well as its effect on the buildings typical use. Hence, the locations where the operations take place need to be strategically defined in order to maximize the beneficial effect of the retrofit. The selection can performed either manually using specific guidelines that describe the approach with the maximum efficiency, or by automatic optimization algorithms that use a probabilistic approach to select and evaluate different solutions, until an optimum is defined [43-44,56].

2 STRUCTURAL MODELING & ANALYSIS

For the purposes of this work, all buildings are simulated using the OpenSEES software [57]. The steel-concrete composite columns are designed as fully encased I-shaped sections. The longitudinal and transversal reinforcement are considered to be the same for all designs: 10mm bars for longitudinal reinforcement and 8mm stirrups spaced 10cm from center to center. The concrete cover is taken 3 cm from the centroid of the longitudinal reinforcement, while an additional 2cm space is considered from the edges of the steel core. Cover concrete is distinguished from the confined concrete with reduced capacity and ductility. The beams are modeled as purely steel elements and the effect of the composite slab is taken into account indirectly by defining rigid diaphragms on each floor. The cables are modeled using section-defined truss elements. Fiber sections are used for all structural elements, as illustrated in Figure 1, while 10 integration points are defined along their longitudinal axis (local x- axis). The column bases are modeled as moment-restrained.

The 'Concrete01' material is used for both the cover and the confined concrete. The steel beams and the core sections of the composite columns are modeled using the 'Steel01' material, while the 'ReinforcingSteel' material is employed for the longitudinal and transversal bars. The cables installed are modeled using the "ElasticPP" (Elastic – Perfectly Plastic) material with zero capacity in compression. Post-tensioning in the cables is simulated by calculating the initial strain required to shift the stress-strain curve properly. The applicable limit values ensure that the material models employed do not exceed the ultimate strain of the simulated material, as it would affect the accuracy of the modelling.

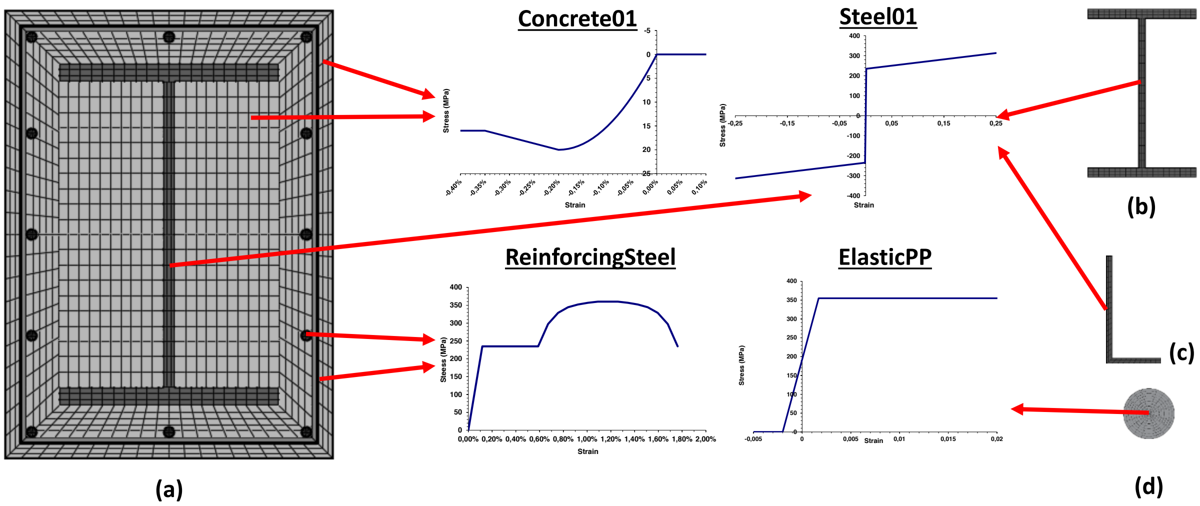

Figure 1: Structural element modeling and discretization into fibers (a) composite column, (b) steel beam, (c) bracing, (d) steel cable

3 RETROFIT AGAINST PROGRESSIVE COLLAPSE

3.1 Damage scenarios

Loss of load-bearing elements is typically the result of extreme events taking place on the structure, such as strong earthquakes, accidents occurring outside or inside the building, or even malevolent human actions. The effect of extreme natural phenomena such as earthquakes on the structure is difficult to be simulated, as their precise characteristics cannot be accurately determined. However, the prediction of the result of accidents or human actions is more straightforward. In this work, two extreme actions are considered: (a) the collision of a heavy loaded truck that causes the loss of a corner column (DS1), another peripheral column (DS2) or multiple neighboring columns (DS3) and (b) an explosion at the base of the building which results in loss of multiple structural elements on two storeys (DS4). The damaged elements are considered to be unable to provide further support to the building and are removed from the model as illustrated in Figures 2 and 3 In DS4 not only columns are damaged, but beams as well, since the blast has a spherical range of effect. The event is assumed to take place instantly and the loads from the failing members are transferred to the neighboring elements which are currently undamaged.

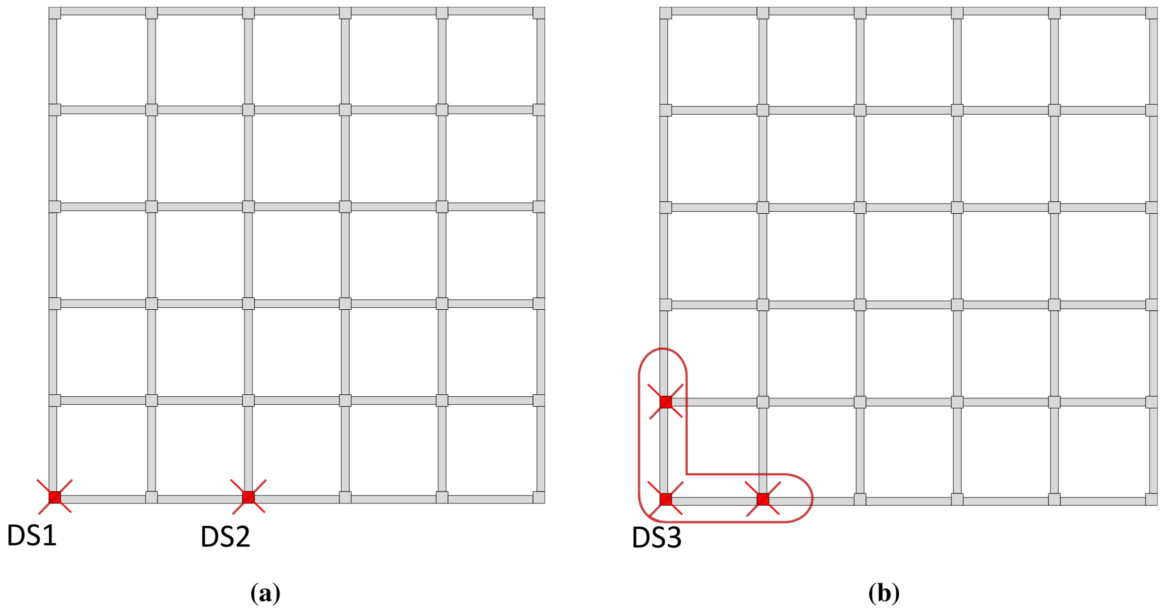

Figure 2: Simulated damage scenarios (a) single-column, (b) multi-column.

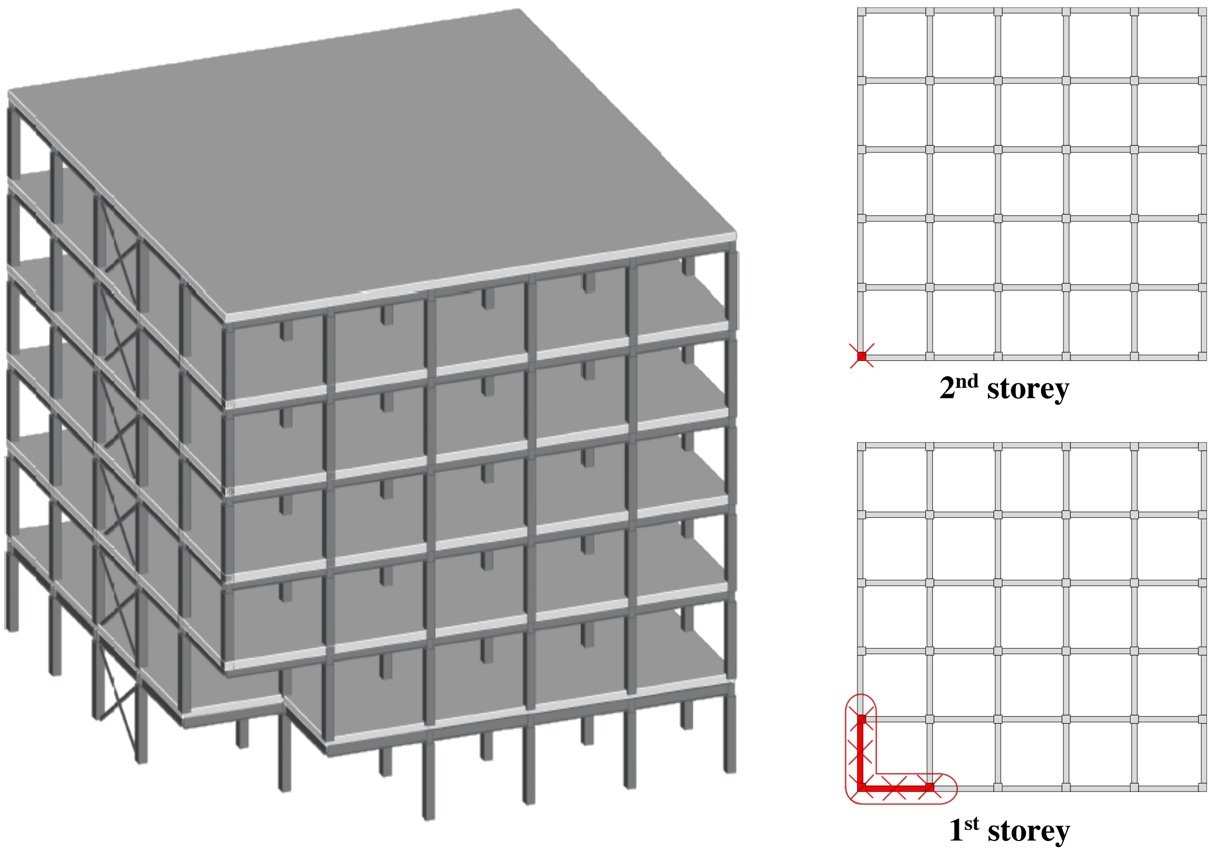

Figure 3: Simulated three-dimensional damage scenario (DS4)

3.2 Design against earthquake and assessment of progressive collapse resistance

The buildings considered in this work need to possess particular characteristics appropriately selected:

(a) they should not be oversimplified or particularly complex, as this might affect the final results,

(b) they should not contain extremely large number of elements, as it would delay the analyses performed without additional benefit to the investigation,

(c) the investigation of various parameters which might affect the efficiency of the retrofit scheme should be possible in each building.

The selected buildings are designed against earthquake according to the provisions of EN 1998 [58]. Steel and composite members are designed according to EN 1993-1-1 [59] and EN1994-1-1 [60] respectively. All buildings have six storeys and consist of five by five bays. The beam span from column center to column center is the same in both horizontal directions. All columns have the same orientation: their major axis is parallel to the global y-axis, so that their flanges are vertical to the global x-direction. Beam-column joints in x-direction are considered to be fixed, forming this way moment resisting frames. Beams on y-direction are simply supported. The required stiffness is provided by bracings installed in the middle bays of both external faces parallel to the y-direction. Five beam spans are considered from 5m to 9m with an increment of 1m. The designs defined are presented in Table 1.

The performance of each building under the considered damage scenarios is assessed according to the provisions of UFC 4-023-03 [53-54]. The maximum plastic rotation at the end of the undamaged beams is used as an indicator for the progressive collapse resistance of the buildings. The results are presented in Table 1.

Beam span (m)	Columns			Beams	Maximum ratio of deflection over span			
	1st-2nd	3rd-4th	5th-6th	All storeys	DS1	DS2	DS3	DS4
5m	HE280B	HE260B	HE180B	IPE270	12,35%	> 50%	> 50%	> 50%
6m	HE300B	HE280B	HE220B	IPE330	> 50%	> 50%	> 50%	> 50%
7m	HE360B	HE280B	HE240B	IPE400	> 50%	> 50%	> 50%	> 50%
8m	HE550B	HE320B	HE260B	IPE450	> 50%	> 50%	> 50%	> 50%
9m	HE600B	HE320B	HE280B	IPE550	> 50%	> 50%	> 50%	> 50%

Table 1: Buildings designed only against earthquake

A recorded ratio of deflection over beam span (vertical drift) larger than 20% indicates high potential for collapse under the simulated damage scenario. Even though the modeling applied in this work is suitable for capturing large deformations, values larger than 50% are particularly large and are considered as strong indication for collapse.

3.3 Retrofit of the deficient buildings

Cables are installed as a means to retrofit the deficient buildings over the bay where the damage occurs. In order to exclude ineffective topologies, one end of the cable needs to be over the top node of a removed column. This end does not necessarily need to be the particular node, but should be indirectly connected, e.g. through the undamaged columns, so that a proportion of the failed column's load can be received by the cable. The location of the second end of the cable may vary within a single bay depending on the intended function:

- In x- and y-direction parallel to the undamaged beams.

- In z-direction parallel to existing columns.
- In x-z and y-z planes installed as bracings.
- In x-y plane installed as horizontal bracings below the slab.

In DS3 and DS4 where more than one bay are affected, all relative locations are taken into consideration. All cables can also be post-tensioned. PT cables in x- and y-direction act as tendons which compress the steel beams so that their deflection is reduced. Selected results are illustrated in Figures 4 to 7. In order to enable the comparison between values referring to different buildings, the deflection ratio (*i.e.* deflection with retrofit over deflection without retrofit) is used in Figures 4 to 6 and the vertical drift (*i.e.* deflection over beam span) in Figure 7. It should be noted that Figures 4 and 5 allow the visualization the effect of the cable system configuration to the modeled buildings. Comparison between the deflection ratios for two buildings in the same figure is not possible.

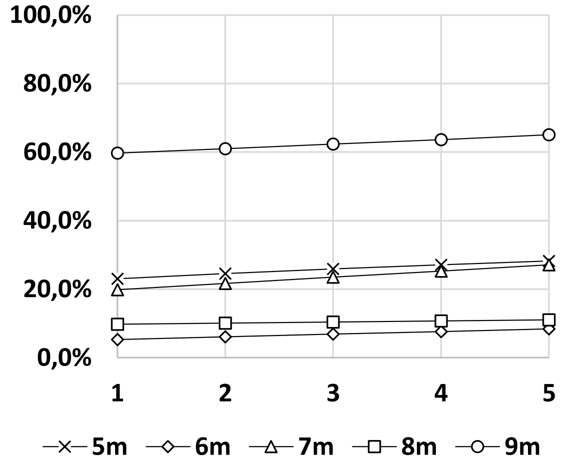

Figure 4: Deflection ratio vs. location of cables in y-z plane (DS1)

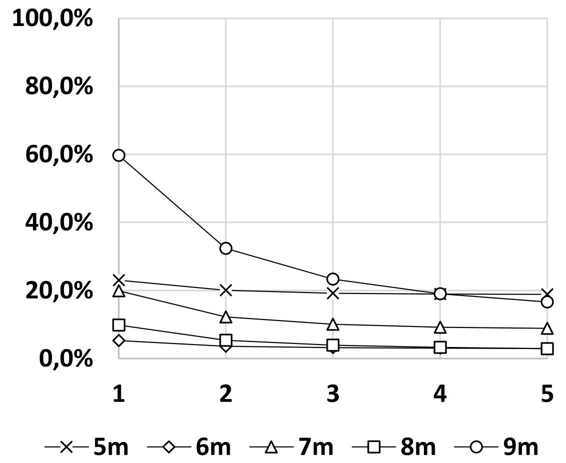

Figure 5: Deflection ratio vs. number of retrofitted bays/storeys – cables in y-z plane (DS1)

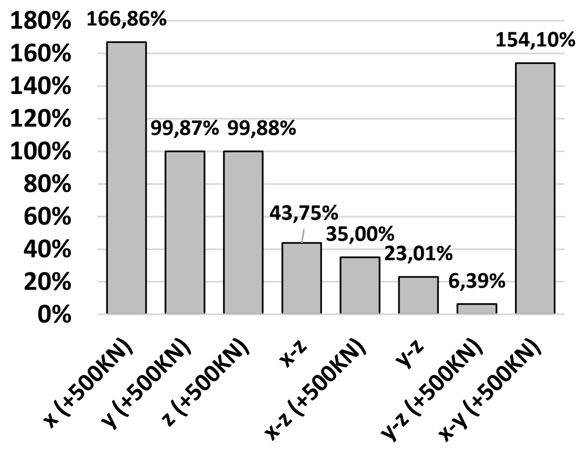

Figure 6: Deflection ratio vs. cable direction (value in parenthesis: post-tensioning applied)

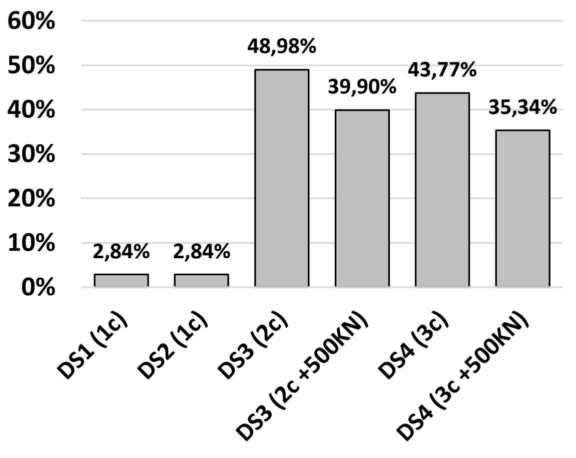

Figure 7: Vertical drift for beam span 5m (values in parenthesis: number of cables + post-tensioning)

The effectiveness of a configuration is related to the damage scenario modeled. Damage scenarios that affect more structural elements require increased number of cables. Post-tensioning has a beneficial effect in all simulated damage scenarios when cables are installed in x-z and y-z planes which is proportional to the applied force. It is also remarkable that the vertical drift recorded for DS1 and DS2 (illustrated in Figure 7) when one cable is installed is the same. The load applied on the top of the failed node is twice as much as the one in DS1. However, there are twice as many beams connected to the column, while the cable is installed in the y-z plane, so all contributing elements are symmetrically placed.

Installation of cable in the y-z plane is more advantageous than in the x-z plane. This is due to the beam-column connections modeled. In x-z plane the elements form a MRF which possesses adequate resistance in order to redistribute the loads from the failed column to the neighboring beams on all storeys above it and so limit the deformations. In the y-z plane this does not apply, because all connections are modeled as hinges. The frames on this plane have no collapse resistance, as their stability relies entirely on the columns, with the exception of the middle bay where bracings are installed. Failure of a column results in free movement of the bays above and which would results in partial collapse of the frame if there was no contribution of the beams in the x direction. Installation of a diagonal element in tension (*i.e.* the cables in this work) forms a truss-type structure which substitutes the missing column and restores the stability of the frame. Moreover, when a single damage scenario is considered, solutions with cables of increased yielding stress are favored, while for multiple damage scenarios this is a disadvantage, as the solution depends mainly on the overall distribution of the cables.

Cables installed in x and y directions and the x-y plane seem to offer no additional assistance in the limitation of the vertical deflections, as the end of the beam over the damaged column also moves towards the neighboring columns, so the distance between the two ends of the cable reduces. Moreover, when post-tensioning force is applied its effect is either minor or negative. It is because of the additional moment applied on the beams due to the large deflection and the post-tensioning force, which causes extra deformation to the beam.

Of particular interest is the effect of cables installed in z direction. The purpose of such an addition is be to aid the columns in receiving the load and transferring it to the beams. When cables are not post-tensioned, the deflection recorded is not altered. This is a strong indicator that the column capacity in tension is particularly larger than it is required, so an additional steel area as small as that of a cable makes no substantial difference. When post-tensioning is applied, the force is mainly received by the column which is in compression. Thanks to the change in its internal forces, the concrete contributes as well to its stiffness, which would be advantageous when designing against earthquake, but its contribution to the building's progressive collapse resistance is negligible. It is evident that in the damage scenarios typically anticipated, the capacity of the columns suffices for the role they play in the alternate path, so the retrofit scheme selected should focus on enhancing the capacity of the beams or receiving a proportion of the extra loads.

The location of the cable seems to affect the deflection of the beams connected to the top of the failed column as well, regardless of the plane they are installed in (x-z or y-z). This is related to the alternate load path developed. When cables are connected directly to the top of the damaged column, a large proportion of the loads is transferred through them to the structural elements of the undamaged bays. If cables are installed one storey above, they are still included in the load path, but at the same time, as the loads are transferred through the column, an increased proportion is received by the additional beams below the location of the cable. Hence, as the distance of the cables from the top of the damaged column increases, their contribution in the alternate load path is reduced. Nevertheless, the reduction in the effectiveness is minor compared to their beneficial effect, so a retrofit scheme based on suspension of the loads on the damaged bay through the columns to the cables could be particularly advantageous when multiple scenarios are taken into account.

An increased number of cables results in a reduction to the deflection recorded. However, the reduction is not proportional as the contribution of the additional cables is related to their location compared to the damaged column, as indicated before. Nevertheless, cables installed in multiple storeys can capture potential damage which occurs on storeys above the one considered (e.g. a gas explosion such as the one that caused the collapse of the Ronan Point building [61]).

4 APPLICATION ON STRUCTURAL OPTIMIZATION

An application that can take advantage of the results of this work is the determination of suitable penalty functions in structural optimization. Structural design optimization is a topic of particular interest, as it allows engineers to define solutions with minimum cost in problems with particularly large number of variables, where manual seek of the solution is impractical. Such problems include the sizing of individual members (sizing optimization problems), the selection of the most efficient placing of structural members (topology optimization) or a combination of both in order to achieve a single or multiple goals at the same time (multi-objective optimization). The existing literature is rich of papers proposing and applying optimization algorithms in structural problems [62-78].

In this section, a mixed sizing-topology discrete optimization problem is defined. A building of those presented in Table 1 (*i.e.* the 5m building) needs to be retrofitted in order to be able to sustain the aforementioned damage scenarios DS1 and DS3 without its beams exceeding the deflection limit defined for low requirements in UFC 4-023-03 [53-54], *i.e.* 20% of the total beam span. Cables can be installed in all bays of the building, but they may not change its internal plan configuration (they cannot be installed in planes x-z and y-z internally). Should each cable be designed independently, this would result in 1230 variables with various characteristics. In order to limit this number to a more manageable one, (a) a maximum number of 20 cables can be installed anywhere in the building, (b) their total area may differ using standard sizes and (c) cables should be installed symmetrically. Taking all aforementioned into consideration, the number of independent variables reduces to 10.

Two optimizations were performed: one allowing the free selection of each alternative and one where solutions with configurations that were found in the previous section to be less effective than their counterparts would be properly penalized. They can be summarized as follows:

- Cables on higher bays are favored by reducing the cable's cost in the objective function. The purpose of this function is to take into account that they create an alternate path that is effective against damage scenarios not considered in the optimization, which is a desirable property, even though it is not required in the particular problem.
- Cables installed in bays that were found to be ineffective in the previous section, such as the middle bays on each side are penalized by increasing the cable's cost in the objective function.
- Cables connecting to at least one common node are penalized by increasing the cost of the cable with the smaller cross-sectional area, in order to avoid solutions that are fit only for the investigated damage scenarios. In case of cables with the same size, one of them is randomly selected. If two cables are installed in the same location, *i.e.* both their ends coincide, the penalty function receives its maximum value which is 20 times the weight of a cable designed using the largest size available.
- Cables installed in a direction that is expected to create compression to the cable are penalized by multiplying their cost by a large value (here it is 10). These solutions are not totally discarded, as they might be effective against damage scenarios not considered or form an alternate path not anticipated, so that they are finally in tension.

- Cables installed in a direction that occupies an internal bay are replaced by random selection of another configuration. This is a problem-specified restriction.

The optimization procedure described in [70] was modified appropriately for the purposes of this work. The results are illustrated in Figure 8.

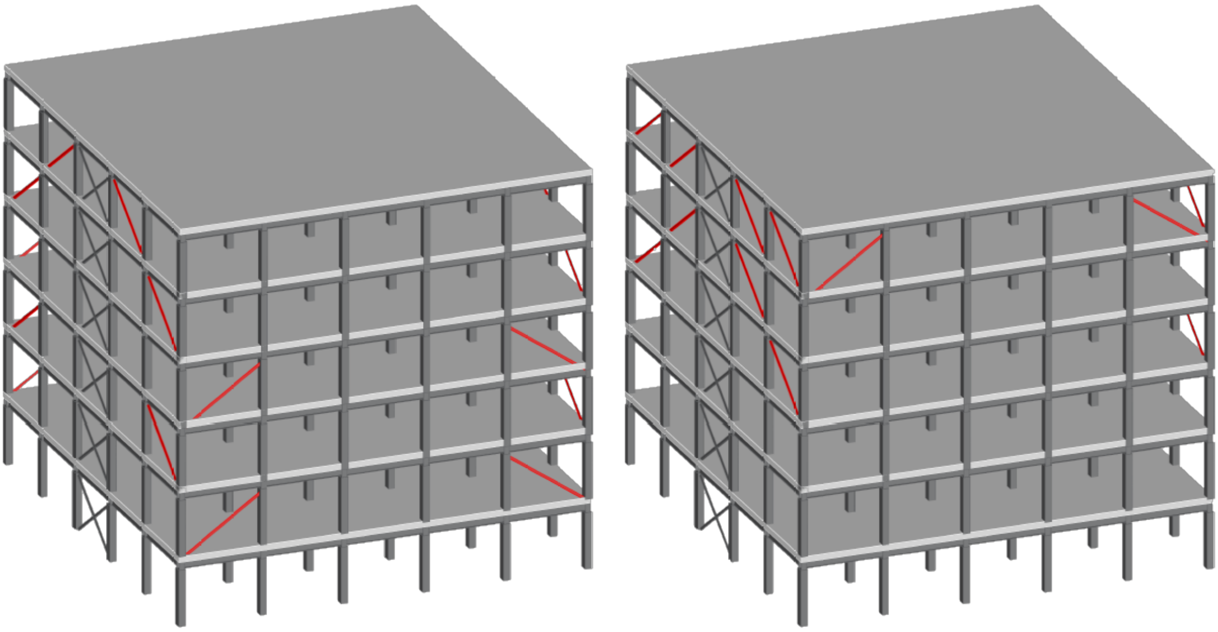

Figure 8: Optimized retrofit (a) without penalty functions (OPT1) and (b) using penalty functions (OPT2). The installed cables are illustrated with thick red lines.

Maximum recorded vertical drift for the optimized designs is 19.46% for OPT1 and 19.80% for OPT2. Both values are indicative of an optimum reached, as they are close to the constraint applied (20%) and further reduction of the total cost could potentially lead to exceeding vertical drifts.

In both solutions, no cables are installed in the middle bays. Their contribution to the collapse resistance of the buildings is negligible for the considered damage scenarios, so this penalty function can be omitted, as the solution is expected to have increased cost compared to others evaluated by the optimization algorithm. However, it has been noticed that, due to the probabilistic selection of candidate solutions, unless it taken into consideration there is always a possibility that this might lead to the selection of a local minimum.

Cables in OPT1 are installed in various storeys. Cables are installed in the lower storeys where their effectiveness against the simulated damage scenarios is increased. Two out of five cables available for each quarter of the building are installed in the x-z plane that is not as effective as the y-z plane. There is one cable installed in each storey above the location of the damage. The advantage of this configuration is that it could be effective for simultaneous loss of two columns, e.g. in the 1st and 3rd storey, while in OPT2 there is no cable to offer additional collapse resistance.

In OPT2 there is a concentration of cables on the top storeys, as intended. One out of five cables is installed in the x-z plane, even though this is not preferred. Further investigation indicates that the particular cable’s contribution is not related with DS1, but with DS3. It can be observed that in the top storey is formed a truss-type mechanism. The remaining two cables are in the same direction and connect at one end; a similar configuration is formed in OPT1 as well. This creates a tie from the corner of the building to the middle bay on this side that has increased stiffness due to the bracings installed.

Comparison between the two designs illustrates the effect of the penalty functions used in the definition of the final design. It is remarkable that, while for OPT1 the configuration seems to have an inherit randomness, in OPT2 a pattern starts to develop: a truss belt is constructed on the top storey and a diagonal tie which reaches up to the enhanced zone created at the top of the building. Nevertheless, it should be noted that further investigation is required in order to propose an optimization framework for the retrofit of composite buildings against progressive collapse.

5 CONCLUDING REMARKS

- The consequences of damage scenarios involving a single element or neighboring elements can be mitigated by retrofit schemes that are focused on the area above the affected bay. However, when multiple scenarios are considered, a more generalized solution needs to be sought.
- The number of bays affected by the retrofit operation can be limited using cables of increased load bearing capacity. Still, when the overall robustness of the building needs to be enhanced, this might not be feasible.
- Installation of cables on the top storeys of the buildings renders them less efficient than installation directly above the damaged columns, but it can also capture damage on the columns above the bay where the failure is expected to occur. So, considering its overall effect, creating an alternate load path that utilizes the existing structural elements is more advantageous than focusing on the most expected damage scenarios.
- In problems with a large number of variables, use of an automatic optimization algorithm can provide solutions with reduced total cost than manual techniques. A suitable use of the applied penalty functions reduces the possibility of yielding configurations that are local minima. The calibration of the penalty functions should be performed for each problem independently based on the intended outcome.

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