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A retrofitting method for torsionally sensitive buildings using evolutionary algorithms

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Abstract. A new method is suggested for the retrofitting of torsionally sensitive buildings. The main objective is to eliminate the torsional component from the first two natural modes of the structure by properly modifying its stiffness distribution via selective strengthening of its vertical elements. Due to the multi-parameter nature of this problem, state-of-art optimization schemes together with an ad-hoc software implementation were used for quantifying the required stiffness increase, determine the required retrofitting scheme and finally design and analyze the required composite sections for structural rehabilitation. The performance of the suggested method and its positive impact on the earthquake response of such structures is demonstrated through benchmark examples and applications on actual torsionally sensitive buildings.

Keywords: structural optimization; evolutionary algorithms; retrofitting method; torsional sensitivity; R/C jackets

1. Introduction

Global Optimization is the application of various numerical procedures for optimizing a problem in order to satisfy a predefined goal. The algorithms used for the optimization process may follow deterministic, stochastic or heuristic-metaheuristic strategies (Hendrix and G.-Tóth 2010). Applications of these optimization algorithms can be found in many scientific fields, including structural engineering. According to Christensen and Klarbring (2008), *structural optimization* is the application of those techniques in the design process of structural members so as to achieve the optimum result, given the constructional and economic limitations. As described in Manoharan and Shanmuganathan (1999), many search mechanisms can be implemented in Structural Optimization, including the Evolutionary Algorithms (EAs) which use heuristic strategies and biology-inspired mechanisms to provide the optimum solution to the defined problem (Leps 2004).

There are plenty of EAs that can be used in structural design problems as shown in Kicinger *et al.* (2005) and Papadrakakis *et al.* (2001) and despite their variety, they all share the same problem formulation, necessary for the structural optimization to be implemented. Their requisites, as described in Haftka and Gurdel (1992), are the following:

- Design variables: All parameters that affect and influence the defined problem.
- Objective function: A function of design variables representing the problem to be optimized resulting a single value to be minimized or maximized for the process to be successful.
- Constraints: Limitations considering the variables of the problem. It is a critical issue, since it allows for the provision of realistic and constructible solutions.

Over the last decades, many researchers worked on structural optimization e.g., Coello *et al.* (1997) who developed a genetic algorithm for the design of concrete beams and Koumousis and Arsenis (1998) who applied genetic algorithms for the detailing of R/C beam sections taking the weight, uniformity and number of steel bars into consideration. Another work on this field is by Leps and Sejnoha (2003), where design of reinforced concrete beams is optimized, using economic criteria expressed by the volume of the concrete, the weight of the steel bars and their price per unit volume and per kilogram respectively. Moreover, a similar optimization method for the flexural design of R/C concrete frames is developed in Camp *et al.* (2003), which complies to the American Concrete Code (ACI 318-14, 2014). Apart from beam sections, such algorithms can be used for the optimal design and detailing of R/C columns under biaxial bending, so as to achieve maximum capacity and economical design (Rafiq and Southcombe 1998).

Furthermore, heuristic optimization techniques were used in fields other than R/C building design e.g., Perea *et al.* (2008) who dealt with the economic design of R/C box frames used in bridge engineering, Martinez *et al.* (2010), who worked on the efficiency of three heuristic algorithms (including EAs) in the low-cost design of R/C bridge piers with rectangular hollow sections, while Hasançebi (2007b, 2008) attempted to optimize the shape and topology configuration of truss bridges. Metaheuristic search techniques can be used in such topology problems like the optimal design of real size pin jointed structures (Hasançebi *et al.* 2009). Finally, Plevris *et al.* (2012) published a review

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of structural optimization applications in the field of earthquake engineering, proving the efficiency of those techniques in handling complicated problems regarding the earthquake resistant design of R/C buildings and bridges.

Structural Optimization is not limited to R/C structures, as it can be implemented in the optimal design of truss and steel structures (Erbatur *et al.* 2000, Charalampakis 2016) and the evaluation of the existing seismic design procedures for frame structures (Lagaros *et al.* 2006). More recently, Shayanfar *et al.* (2014) developed a reliability-based design method for such structures while Zachaneraki *et al.* (2013) introduced an algorithm for the seismic design of steel-moment resisting frames using reliability constraints. These techniques can also be used in the performance-based design of steel structures, allowing the consideration of its inelastic behavior and life-cycle cost (Fragiadakis *et al.* 2006, Fragiadakis and Lagaros 2011, Kaveh *et al.* 2014), while a new metaheuristic optimization algorithm that replaces the trial-and-error method used in the design process was introduced in Fragiadakis *et al*. (2006). Conclusively, the performance of the evolutionary algorithms was tested in the identification of the hysteretic system of bolded-welded steel connections (Charalampakis and Dimou 2013) and in the design of steel frames (Hasançebi 2007a).

The objective of this paper is to expand the use of the EAs in the challenging field of retrofitting of existing R/C structures and particularly to those characterized as torsionally sensitive with an ultimate goal to improve their performance under earthquake loading. In such a structural system, there is usually strong coupling between the torsional and translational component in its fundamental natural mode (Penelis and Penelis 2014). In most cases, these structures are irregular in plan and elevation, according to the criteria described in several Codes e.g. Eurocode 8 - Part 1 (2006); their static and dynamic behavior were demonstrated in an actual 16-story building in Penelis and Papanikolaou (2010). During an earthquake event, these irregularities might lead to excessive drifts at the perimeter columns and increase the possibility of structural failure to the abovementioned and adjacent buildings due to pounding effects (Penelis and Penelis 2014, Gokdemir *et al*. 2013). In an attempt to eradicate this phenomenon, Lagaros *et al*. (2006) proposed a design method, based on evolutionary algorithms, where the size of the vertical elements is optimized, so that the eccentricity between the rigidity and mass center is minimized.

In Eurocode 8 - Part 3 (2006) it is suggested that these adverse torsional effects may be accepted if the earthquake actions on structural elements are amplified by a constant factor. On the other hand, the American Standards for Seismic Evaluation and Retrofit of Existing Buildings (ASCE/SEI 41-13, 2013) are more demanding, directing the calculation of a variety of amplification factors for different portions of the building and response actions that can better simulate the effects of the torsional component. In this context, multi tuned-mass-dampers were used to control the mode shape of 3D irregular buildings and constraint the interstory drifts and total accelerations to allowable values (Daniel and Lavan 2014, 2015), as well as techniques that use topology or energy-based optimization to create torsional balance by implementing viscoelastic (Kim and Bang 2002, Garcia *et al*. 2007, Fujita *et al*. 2010a, Paolacci 2013), frictional (de la Llera *et al*. 2007) and viscous fluid dampers (Fujita *et al*. 2010b, Lavan and Levy 2010, Rofooei and Mohammadzadeh 2016) in plan, or seismic isolators (Charmpis *et al*. 2015) in elevation. Moreover, a deterministic methodology for seismic upgrading of torsionally unbalanced buildings was introduced in Thermou and Psaltakis (2015), which attempts to eliminate the torsional component from the building's response shapes and achieve a near-uniform distribution of interstory drifts in elevation.

In the herein proposed method, the increasingly popular evolutionary algorithm of *differential evolution* (DE) is applied to quantify the required strengthening of each vertical element, aiming to restore torsional balance and eliminate any undesirable modal behavior of the structure that can lead to brittle failure under earthquake. It is a relatively recent, population based evolutionary algorithm, introduced by Storn and Price (1997) and has been applied in the optimal design of prestressed and R/C concrete beams (Quaranta and Fiore 2014, Hrstka *et al*. 2003) as well as in the optimal design of planar steel trusses (Fiore *et al.* 2016). Its evolutionary process, along with paradigms that prove its efficiency over other optimization techniques, presented in Price and Storn (2005).

2. Description of the suggested method

The suggested retrofitting method attempts to eliminate the torsional component from the first and second natural modes by strengthening the vertical elements of the structure, conforming with capacity design rules of modern Design Codes, so that these modes will finally become purely translational and respond as an ideal ground motion parallel to two orthogonal axes. Its main advantage among other methods in the literature is that it allows consideration of constructional/architectural and economical limitations in structural simulation and provides, based on these constraints, an optimal earthquake-resistant solution through an optimization procedure incorporating a series of objective function evaluations. It is comprised of three different phases:

- Phase A: Quantification of the required increase of stiffness in each element, in order to eliminate the torsional component from the first and second natural modes.
- Phase B: Dimensioning of the essential concrete jackets in order to meet the stiffness requirements from Phase A.
- Phase C: Section analysis and detailing of the jacketed sections calculated in Phase B.

2.1 Phase A: Optimization procedure

The software framework for implementing Phase A, includes (a) a generic optimization tool using evolutionary algorithms to provide the optimum values for stiffness modification factors (i.e., stiffness increase in each vertical element), (b) a modal analysis software to analyze the structure in the framework of the above evolutionary algorithm and (c) a spreadsheet-based platform for defining all problem parameters and providing a seamless interaction between the first two components. Specifically: (a) XL Optimizer (Fotopoulos and Charalampakis 2015) will perform the optimization process using the DE scheme, (b) SAP2000 (Computers and Structures Inc., 2015) will be used as the eigenvalue solver and (c) REMET (REtrofitting MEthod for Torsionally sensitive buildings), an ad-hoc Microsoft® Excel VBA application will provide the backbone platform for implementing the suggested optimization method.

Before running the optimization process, it is necessary to define the objective function that needs to be minimized. The problem variables are the stiffness modification factors (larger than unity) of all the vertical elements to be strengthened and the objective function (f) is

$$f = \sqrt{R_{z,1}^2 + R_{z,2}^2} \tag{1}$$

where $R_{z,1}$ and $R_{z,2}$ are the 1st and 2nd mode mass participating ratio of the *torsional* global degree of freedom, respectively.

The minimization of the above function will eventually minimize the torsional component of the structure and transform the first two mode shapes into a purely translational form. In case of multistory buildings, the corresponding number of variables (i.e., stiffness modifiers) are inevitably high, which increases the number of possible configurations (and eventually corresponding objective function values) to a prohibitive number for a manual trial-end-error practice, hence suggesting the use of an automated optimization tool. Furthermore, it is critical to further apply constraints among different variables, in order to provide a realistic and constructible solution (e.g., the thickness of the R/C jackets should remain constant, or decrease, in elevation).

A flow chart of Phase A is depicted in Fig. 1. In short, REMET is launched and initializes the building model, providing the structural properties shown in Tables 1-2. As long as REMET is running in the background, a scenario analysis that is based on the above information is created in XL Optimizer, where the user defines the parameters of the optimization procedure. When the scenario is launched, the DE optimization algorithm continually modifies the values of the defined variables. Simultaneously, REMET automatically assigns these updated values to the corresponding modification factors into the analysis model (using SAP2000 API commands) and executes a new modal analysis for updating the objective function value.

This procedure is repeated until the termination criteria are satisfied and the optimum solution is retrieved. The number of vectors at each generation is 50, due to the complexity of the problem, while the chosen DE optimization scheme, for all the examined cases in this paper, is the most robust (rand/1/bin). The mutation scale factor (F) is set to 0.5 because values close to 0 create less diverse populations that can lead to premature convergence, while on the other hand, values near unity reduce the number of mutants leading to erratic convergence. Furthermore, the Cr parameter that forms the trial vector based on the mutant vector, is set to 0.9, because lower values cause overwhelming of data and greater ones loss of diversity (Storn and Price 1997).

Fig. 1 Flowchart of Phase A

Table 1 Typical information provided for the vertical structural elements

Story	Columns	Name	z_{min}	z_{max}	L_x	L_y	I_{xx}	I_{yy}
Ground floor	C1	C60X60	0	3	0.6	0.6	1	1
Ground floor	C2	C60X60	0	3	0.6	0.6	1	1

z_{min} : bottom elevation of the element
z_{max} : top elevation of the element
L_x, L_y : dimensions parallel to x and y axis, respectively
I_{xx}, I_{yy} : moment of inertia modifiers of each element

Table 2 Typical objective function and modal analysis results for the first three modes

Modal participating mass ratios			
	UX	UY	RZ
1st mode	0.999	0.000	0.001
2nd mode	0.000	0.999	0.001
3rd mode	0.001	0.001	0.998
Objective function		0.001	

UX, UY, RZ: Degrees of freedom

2.2 Phase B: Design of R/C jackets

When the optimization process is completed, the result has the form of a set of new stiffness modification values for each vertical element. Phase B is then handled by REMET, which converts this stiffness increase for each element to reinforced concrete jackets of specific thickness in each direction.

The necessary user provided data for this phase, are (a) the concrete class of the R/C jacket and (b) the R/C jacket type (e.g., full or partial). Afterwards, REMET combines this information with the results of Phase A in order to calculate the final dimensions of the composite section.

Specifically, if a is the modification factor for I_{xx} and b for I_{yy}, the equilibrium system to be solved is

$$\begin{aligned} E' \cdot I'_{xx} &= a \cdot E \cdot I_{xx} \\ E' \cdot I'_{yy} &= b \cdot E \cdot I_{yy} \end{aligned} \qquad (2)$$

where:
E': Equivalent modulus of elasticity of the jacketed section
E: Modulus of elasticity of the core (initial) section
I'_{xx} , I'_{yy}: Moments of inertia of the jacketed section
I_{xx} , I_{yy} : Moments of inertia of the core (initial) section

If t'_x and t'_y are the thicknesses of the jacketed section and t_x, t_y those of the core section, then Eq. (2) is formed as below

$$\frac{t'_y \cdot t'^3_x}{12} = a \cdot \frac{E}{E'} \cdot \frac{t_y \cdot t^3_x}{12} \quad , \quad \frac{t'_x \cdot t'^3_y}{12} = b \cdot \frac{E}{E'} \cdot \frac{t_x \cdot t^3_y}{12} \qquad (3)$$

Depending on the geometry of the jacket, the above system can either be solved or not. Especially, when $t'_y = t_y$ or $t'_x = t_x$ the system is solvable, albeit in any other case there are three unknown variables (t'_x, t'_y and E') and two equations, so an assumption must be made considering the value of E'. A reasonable assumption, is that the core section covers the 90% of the composite section's area while the rest 10% is the R/C jacket. Since the more area a material covers, the greater the impact on the modulus of elasticity of the jacketed section, its value equals to

$$\begin{aligned} A_c &= \frac{(\text{core section's area})}{(\text{jacketed section's area})} = 0.9 \\ A_j &= \frac{(\text{jacket's area})}{(\text{jacketed section's area})} = 0.1 \end{aligned} \qquad (4)$$

$$E' = A_c \cdot E + A_j \cdot E_j = 0.9 \cdot E + 0.1 \cdot E_j \qquad (5)$$

where E_j is the Modulus of elasticity of the jacket material.

In order to verify the above assumption, the procedure shown in Fig. 2 is followed.

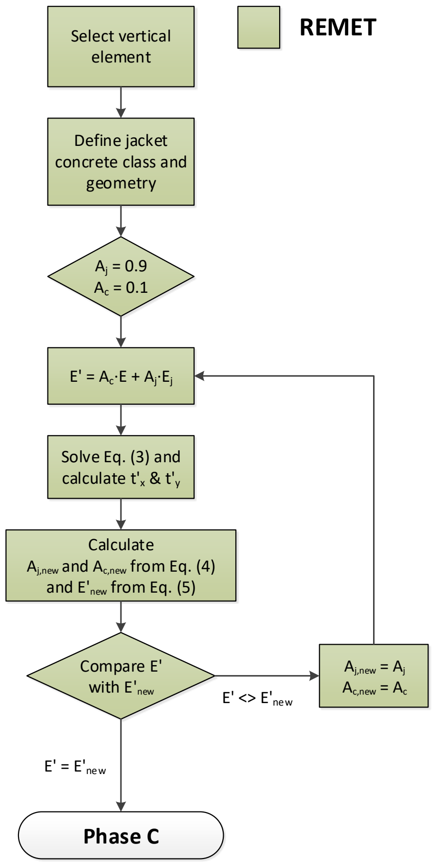

Fig. 2 Flowchart of Phase B

2.3 Phase C: Analysis of the jacketed sections

The final phase of the method covers the analysis of the jacketed sections created in Phase B (Fig. 3) (Papanikolaou *et al.* 2012). It is herein necessary to define the longitudinal steel reinforcement of the core and jacketed section, the steel class and the reinforcement cover. This information is user provided in REMET, which creates a data file that is imported in the section analysis software AnySection

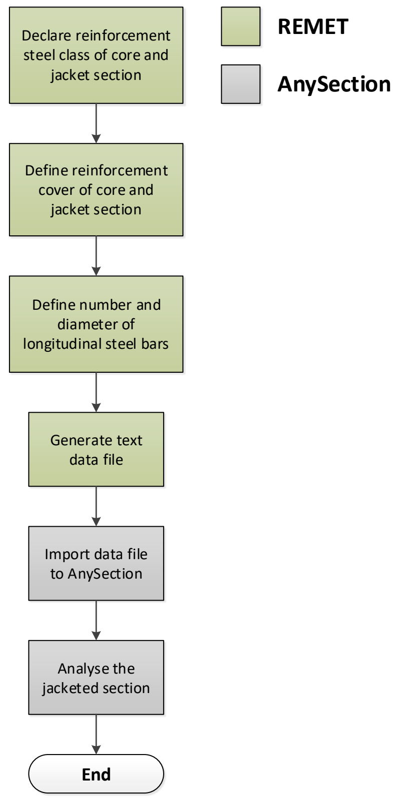

Fig. 3 Flowchart of Phase C

(Papanikolaou 2015), so that the designer can analyze the sections and decide on the retrofitting scheme.

3. Validation of the suggested method

In order to validate the performance of the optimization procedure, the method is applied to two benchmark buildings (B1 and B2). In the first case, the problem of creating torsional balance is first solved by hand calculations and the closed-form solution is later compared to the optimization process while in the second, the suggested method and another methodology are implemented on the same building, so as to compare their outcomes.

3.1 Benchmark building B1

Benchmark building B1 is a reinforced concrete single story space frame structure with diaphragm action at the slab level. The objective of this example is to test the proposed method in a complex building with a high number of variables and constraints. Specifically, there are 25 beams (0.25×0.60 m) and 18 column sections (0.80×0.80 m and 0.25×0.25 m), with the larger ones located on the left side of the plan, as shown in Fig. 4. This configuration increases the distance between CR (center of rigidity) and CM, in both directions and eventually amplifies torsional effects. The mass of B1 is assumed to be lumped at the CM and its value sources from the seismic load combination G+0.3Q (Eurocode 8-1, 2004), where G=0.5 kN/m^2 and Q=2 kN/m^2 (Eurocode 1-1, 2004).

$$\mathbf{M}=\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & J_m \end{bmatrix}=\begin{bmatrix} 268.9 & 0 & 0 \\ 0 & 268.9 & 0 \\ 0 & 0 & 28657.7 \end{bmatrix} \tag{6}$$

3.1.1 Hand calculations

In order to achieve torsional balance, CM has to coincide with CR, hence the smaller columns are strengthened in one or both directions. It is decided that columns C8, C9, C10, C17 and C18 will be equally strengthened in their y-direction (to achieve x_s=0) while C4, C5, C13 and C14 will be equally retrofitted in both directions. The required modification factors, for x_s and y_s to be equal to zero, are calculated below

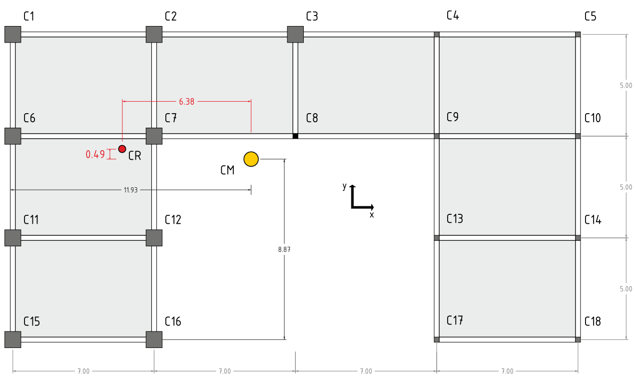

Fig. 4 Plan configuration of building B2

$$\begin{aligned} & x_s=0 \Rightarrow \sum_i x_{Ci}\cdot K_{yy}^{Ci}=0 \Rightarrow \\ & \Rightarrow -11.93\cdot\left(K_{yy}^{C1}+K_{yy}^{C6}+K_{yy}^{C11}+K_{yy}^{C15}\right)-4.93\cdot\left(K_{yy}^{C2}+K_{yy}^{C7}+K_{yy}^{C12}+K_{yy}^{C16}\right)+ \\ & +2.07\cdot\left(K_{yy}^{C3}+K_{yy}^{C8}\right)+9.07\cdot\left(K_{yy}^{C4}+K_{yy}^{C9}+K_{yy}^{C13}+K_{yy}^{C17}\right)+ \\ & +16.07\cdot\left(K_{yy}^{C5}+K_{yy}^{C10}+K_{yy}^{C14}+K_{yy}^{C18}\right)=0 \end{aligned} \tag{7}$$

Due to the fact that all columns share the same material and height, Eq. (7) is reduced to

$$\begin{aligned} & -11.93\cdot\left(4\cdot I_{xx}^{C80X80}\right)-4.93\cdot\left(4\cdot I_{xx}^{C80X80}\right)+2.07\cdot\left(I_{xx}^{C80X80}+I_{xx}^{'}\right)+ \\ & +9.07\cdot\left(4\cdot I_{xx}^{'}\right)+16.07\cdot\left(4\cdot I_{xx}^{'}\right)=0 \Rightarrow \\ & \Rightarrow I_{xx}^{'}=0.261\ m^4 \end{aligned} \tag{8}$$

Thus, the necessary I_{xx} modification factor value, for each jacketed column is

$$a=\frac{I_{xx}^{'}}{I_{xx}^{C25X25}}=\frac{0.261}{3.9\cdot 10^{-3}}=66.9 \tag{9}$$

The same procedure is followed in order to calculate the necessary I_{yy} modifier

$$\begin{aligned} & y_s=0 \Rightarrow \sum_i y_{Ci}\cdot K_{xx}^{Ci}=0 \Rightarrow \\ & \Rightarrow -8.87\cdot\left(K_{xx}^{C15}+K_{xx}^{C16}\right)-8.87\cdot\left(K_{xx}^{C17}+K_{xx}^{C18}\right)-3.87\cdot\left(K_{xx}^{C11}+K_{xx}^{C12}\right)- \\ & -3.87\cdot\left(K_{xx}^{C13}+K_{xx}^{C14}\right)+1.13\cdot\left(K_{xx}^{C6}+K_{xx}^{C7}+K_{xx}^{C8}+K_{xx}^{C9}+K_{xx}^{C10}\right)+ \\ & +6.13\cdot\left(K_{xx}^{C1}+K_{xx}^{C2}+K_{xx}^{C3}+K_{xx}^{C4}+K_{xx}^{C5}\right)=0 \Rightarrow \\ & \Rightarrow -8.87\cdot\left(2\cdot I_{yy}^{C80X80}\right)-8.87\cdot\left(2\cdot I_{yy}^{C25X25}\right)-3.87\cdot\left(2\cdot I_{yy}^{C80X80}\right)-3.87\cdot\left(2\cdot I_{yy}^{'}\right)+ \\ & +1.13\cdot\left(2\cdot I_{yy}^{C80X80}+3\cdot I_{yy}^{C25X25}\right)+6.13\cdot\left(3\cdot I_{yy}^{C80X80}+2\cdot I_{yy}^{'}\right)=0 \Rightarrow \\ & \Rightarrow I_{yy}^{'}=0.450\ m^4 \end{aligned} \tag{10}$$

$$b=\frac{I_{yy}^{'}}{I_{yy}^{C25X25}}=\frac{0.450}{3.9\cdot 10^{-3}}=115.4 \tag{11}$$

3.1.2 Optimization procedure

The variables of this problem are the I_{xx} modifiers of columns C4, C5, C8, C9, C10, C13, C14, C17, C18 and the I_{yy} modifiers of columns C4, C5, C13 and C14. It was assumed, during the hand calculations, that these columns are equally retrofitted in each direction and as a result a constraint assuring the equality of the I_{xx} and I_{yy} modifiers is imposed. The permissible value range is set to 1~200, convergence is reached after 500 evaluations and the results are shown in Tables 3-4.

The stiffness modifiers from the hand calculations are identical to the above values while the torsional component (initially 49%) was totally removed from the first two modes of building B1, hence the validation process is deemed successful.

3.2 Benchmark building B2

Benchmark building B2 is a one-story concrete space frame structure, originally presented as a benchmark example for an optimization method of torsionally unbalanced systems (Lagaros *et al.* 2006), where an as-built solution from an experienced structural engineer is compared with an optimization procedure. In this context B2 is considered as an existing R/C building, with 9 columns (0.25×0.25 m) as shown in Fig. 5, and the concrete class of both the structure and the R/C jackets is C20/25, so that the results of a design and a retrofitting method are comparable. The general principles implemented in the previous example (building B1) are also applied in this case.

The architectural constraints presented in Lagaros *et al.* (2006) are considered by selecting the appropriate modifiers as the variables of the optimization procedure and especially I_{xx} for C2, C3, C4, C6, C9 and I_{yy} for C1, C5, C7, C8, C10. The variables range is set to 1~200, convergence is reached after 500 evaluations and the results of the proposed method, proving its efficiency over the initial applied solution, are shown in Tables 5-6.

Table 3 Results of the optimization procedure for building B1

Story	Columns	Name	I_{xx}	I_{yy}
Ground floor	C1	C80X80	1.0	1.0
Ground floor	C2	C80X80	1.0	1.0
Ground floor	C3	C80X80	1.0	1.0
Ground floor	C4	C25X25	**66.9**	**115.4**
Ground floor	C5	C25X25	**66.9**	**115.4**
Ground floor	C6	C80X80	1.0	1.0
Ground floor	C7	C80X80	1.0	1.0
Ground floor	C8	C25X25	**66.9**	1.0
Ground floor	C9	C25X25	**66.9**	1.0
Ground floor	C10	C25X25	**66.9**	1.0
Ground floor	C11	C80X80	1.0	1.0
Ground floor	C12	C80X80	1.0	1.0
Ground floor	C13	C25X25	**66.9**	**115.4**
Ground floor	C14	C25X25	**66.9**	**115.4**
Ground floor	C15	C80X80	1.0	1.0
Ground floor	C16	C80X80	1.0	1.0
Ground floor	C17	C25X25	**66.9**	1.0
Ground floor	C18	C25X25	**66.9**	1.0

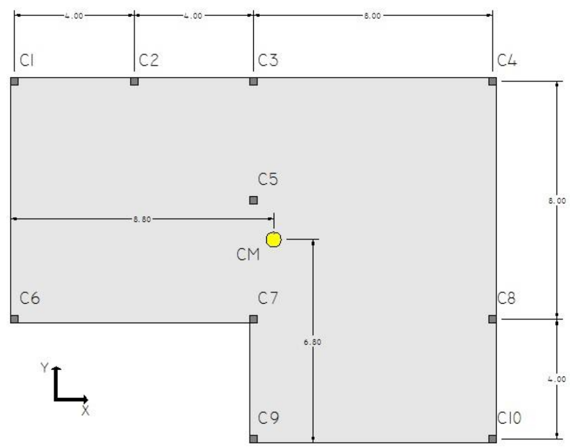

Fig. 5 Plan configuration of building B2

Table 4 Results of modal behavior for building B1

	Before			After		
	Modal participating mass ratios			Modal participating mass ratios		
	UX	UY	RZ	UX	UY	RZ
1st mode	0.00	0.51	0.49	**1.00**	0.00	0.00
2nd mode	0.99	0.01	0.00	0.00	**1.00**	0.00
3rd mode	0.00	0.49	0.51	0.00	0.00	**1.00**
Objective function		0.49			0.00	

Table 5 Results of modal behavior for Building B2

	Applied solution			Optimum solution		
	Modal participating mass ratios			Modal participating mass ratios		
	UX	UY	RZ	UX	UY	RZ
1st mode	0.38	0.48	0.14	**1.00**	0.00	0.00
2nd mode	0.07	0.45	0.00	0.00	**1.00**	0.00
3rd mode	0.05	0.07	0.86	0.00	0.00	**1.00**
Objective function		0.14			0.00	

Table 6 Size of the R/C jackets for building B2

Story	Columns	Name	h_x (cm)	h_y (cm)
Ground floor	C1	C25X25	0.0	119.0
Ground floor	C2	C25X25	20.0	0.0
Ground floor	C3	C25X25	21.0	0.0
Ground floor	C4	C25X25	154.0	0.0
Ground floor	C5	C25X25	0.0	63.0
Ground floor	C6	C25X25	120.0	0.0
Ground floor	C7	C25X25	0.0	78.0
Ground floor	C8	C25X75	0.0	64.0
Ground floor	C9	C25X25	129.0	0.0
Ground floor	C10	C25X25	0.0	77.0

In both optimization methods, the torsional component was removed from the fundamental periods of the structure and early convergence was achieved, during the optimization process. The only notable difference, is that the present solution suggests the implementation of larger vertical elements to reduce the distance between CS and CR to only 0.4 cm, while the design method proposed smaller columns and walls for this distance to be 2.26 cm.

4. Application to an actual torsionally sensitive building

This section deals with a torsionally sensitive, irregular in plan model structure, which was constructed for the SPEAR project (Fardis and Negro 2005); its characteristics are presented in detail in Jeong and Elnashai (2004) and was also analyzed in SAP2000 by Belejo *et al.* (2008) (Fig. 6), but to the best of the Authors' knowledge, this is the first

Fig. 6 Left: Experimental structure, Right: Numerical model

attempt to strengthen the structure and create torsional balance. Specifically, two different retrofitting scenarios are examined and the effectiveness of the method is tested in both cases.

4.1 First case

The retrofitting scenario examined in this the first case, consists of the equal retrofitting of all columns, using equally sized R/C jackets in elevation. Particularly, the design variables are the two stiffness modifiers (I_{xx} and I_{yy}) and their permissible range is set to 1~5, so that the stiffness requirements and, in turn, the thickness of the R/C jackets in each column will be small and cost effective. The constraint imposed to assure the implementation of same sized R/C jackets in elevation, is the equality of the stiffness modifiers along the height of the same element i.e., the I_{xx} modification factor of a column section on the ground floor is equal to the one on the first and second floor. The termination criterion is set to a maximum of 20k function evaluations, with convergence reached at 15k evaluations and the results of Phase A are shown in Fig. 7.

The value of the objective function is dropped to zero and hence the torsional component was totally removed from the first two modes (initially 17.4% and 21.2% respectively, Table 7). It is observed that the final mode shapes are purely translational, yet slightly inclined with respect to the global X and Y directions (Fig. 8). This could be further refined if necessary, by modifying the objective function to zero UY and UX components as well for the first and second mode, respectively. The geometry of the implemented R/C jackets using C25/30 concrete and B500C steel, depends on the modification factors resulted from the optimization procedure and their dimensions calculated in Phase B are shown in Fig. 8.

Table 7 Results of modal behavior for SPEAR building - Case 1

	Before			**After**		
	Modal participating mass ratios			Modal participating mass ratios		
	UX	UY	RZ	UX	UY	RZ
1st mode	0.641	0.074	0.174	0.725	0.121	0.000
2nd mode	0.218	0.435	0.212	0.125	0.706	0.000
3rd mode	0.025	0.323	0.499	0.000	0.000	0.850
Objective function		0.274			0.00	

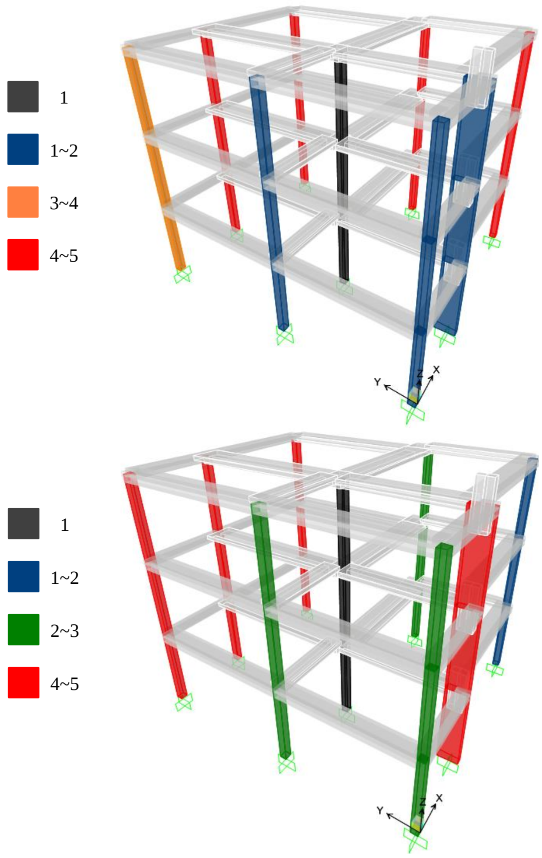

Fig. 7 Left: Ixx modifiers, Right: Iyy modifiers - Case 1

After the completion of Phase B, the necessary reinforcement of the jacketed sections is provided, and the final stage of the method is performed using section analysis software. For instance, in case of column S0C2, the reinforcement in the core section is 4Ø12 while in the jacket is assumed to be 8Ø14. The section is analyzed and finally, in order to evaluate the retrofitting process in terms of the ultimate strength, the volumetric capacity index introduced in Papanikolaou *et al.* (2012) is provided in Fig. 9. It is observed that the method proved to be efficient as the ultimate strength was significantly increased.

4.2 Second case

The second retrofitting scenario is based on the possible construction of wall elements at the perimeter of the building and especially where columns C1 and C3 are located, in order to increase its torsional resistance and eliminate the torsional component from the first two modes. The variables of this case are both stiffness modifiers of columns C1 and C3 and their permissible range is now 1~50, for allowing their dimensions to be significantly increased. The dimensions of the wall elements do not change in elevation, which is specified as an additional constraint (as in case 1). Convergence was reached after 10k evaluations and the results of Phase A are shown in Fig. 10.

The value of the objective function becomes zero while the first and second mode are purely translational and now parallel to the global X and Y axes, as shown in Table 8 and Fig. 11. The size of the wall elements (where C25/30 and B500C is used), depends on the modification factor values resulted from Phase A and it is depicted in Fig. 11.

The retrofitting scheme is concluded with the analysis of the composite sections, calculated above. For instance, in column S0C3 the reinforcement in its core section is 4Ø12 while in the jacket is assumed to be 12Ø14. The result of the retrofitting procedure in the ultimate strength of this section, is demonstrated in Fig. 12.

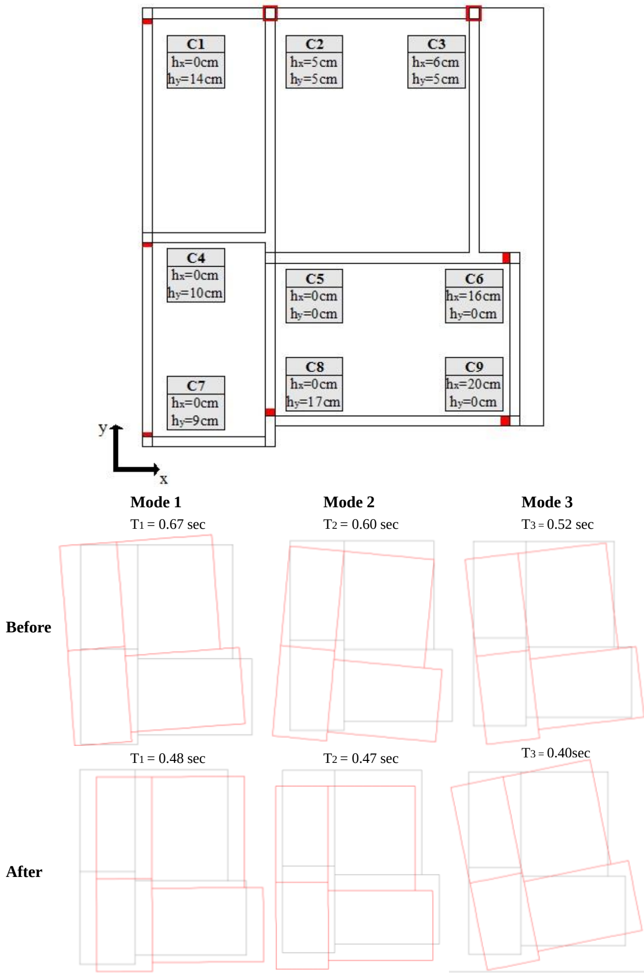

Fig. 8 Left: R/C jacketing, Right: Modal deformed shapes at level *z* = 9 m - Case 1

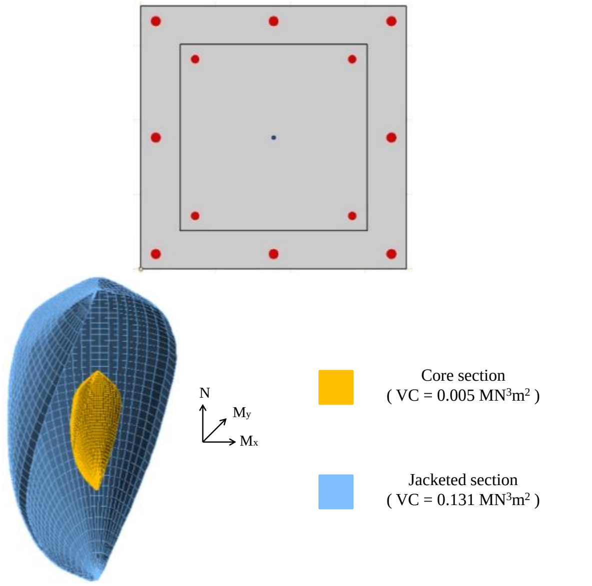

Fig. 9 Left: Jacketed section, Right: 3D failure curves (column S0C2) - Case 1

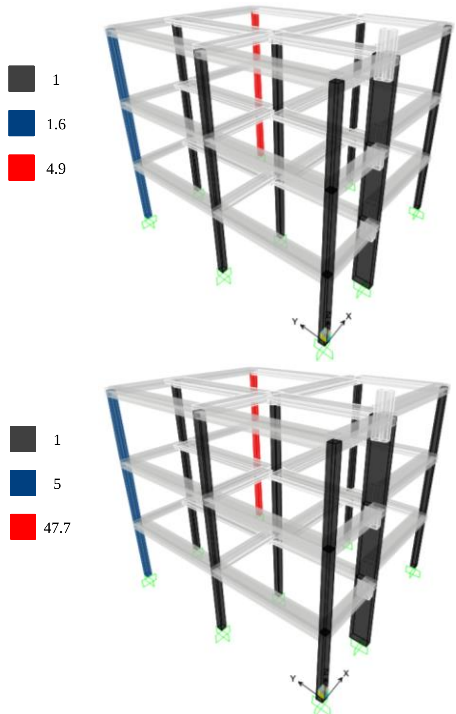

Fig. 10 Left: Ixx modifiers, Right: Iyy modifiers - Case 2

Table 8 Results of modal behavior for SPEAR building – Case 2

	Before			After		
	Modal participating mass ratios			Modal participating mass ratios		
	UX	UY	RZ	UX	UY	RZ
1st mode	0.641	0.074	0.174	0.870	0.000	0.000
2nd mode	0.218	0.435	0.212	0.000	0.801	0.000
3rd mode	0.025	0.323	0.499	0.000	0.000	0.842
Objective function		0.274			0.00	

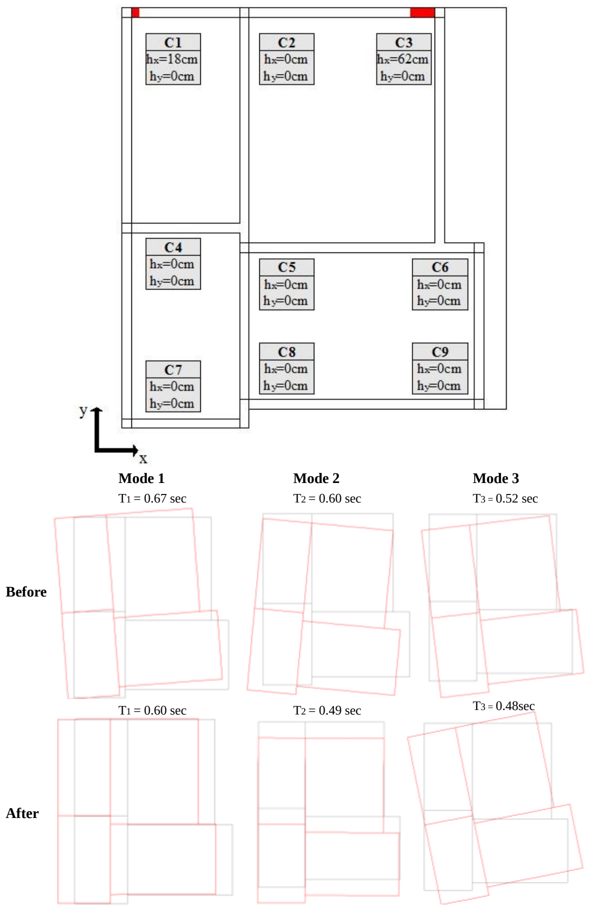

Fig. 11 Left: R/C jacketing, Right: Modal deformed shapes at level z=9 m - Case 2

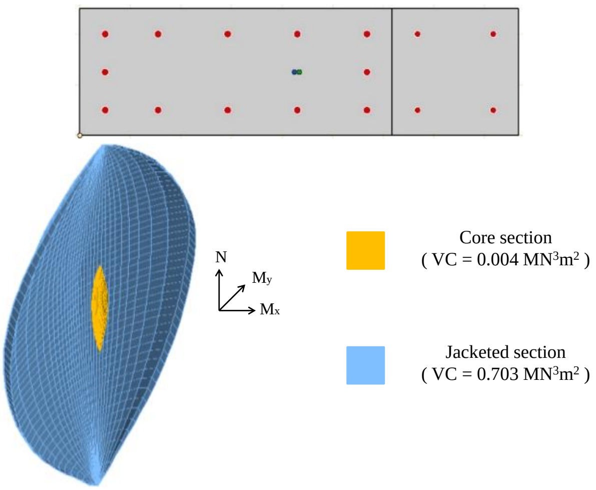

Fig. 12 Left: Jacketed section, Right: 3d failure curves (column S0C3) - Case 2

5. Conclusions

This paper introduced a promising method for the optimal strengthening of torsionally unbalanced buildings using R/C jackets and highlighted the applicability of evolutionary algorithms in the challenging field of retrofitting of existing structures for improving their structural performance under earthquake excitations. The most significant conclusions of this study can be summarized as follows:

- There are no geometric limitations, thus every building can be retrofitted towards the attainment of “torsional balance” at a reasonable computing time. The results of Phase A were validated against theoretical solutions and proved to be accurate, while the required increase of stiffness was successfully converted into R/C jackets.
- The predefined goal of the method was satisfied in the retrofitting scenarios of the SPEAR building, as the value of the objective function became zero in both cases. This fact proves that optimization algorithms can be implemented to improve the modal behavior of existing torsionally sensitive buildings and eliminate the torsional component, decreasing the possibility of brittle failure under earthquake loading.
- The use of constraints is important and has a clear engineering purpose, because they provide the opportunity to better simulate the procedures followed in common practice and adapt the outcome of the method to the requirements of the problem under investigation.

In conclusion, it is believed that whereas considerable research has been performed in the field of structural optimization in the design of new structures, still research on rehabilitation of existing structures through optimization is limited. Hence, the application of global optimization procedures based on evolutionary algorithms such as the herein suggested method should be considered as a promising analytical tool in the above context and should be further pursued.

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