Primljen / Received: 23.1.2021.
Ispravljen / Corrected: 10.5.2020.
Prihvaćen / Accepted: 24.6.2020.
Dostupno online / Available online: 10.2.2023.

Effects of column damage on the reliability of reinforced concrete portal frames

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Research Paper

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The reliability and behaviour of columns belonging to portal-reinforced concrete frames depend on many factors. This paper presents a parametric study of a reliability column in a non-linear domain, considering mechanical variability and targeting damaged areas of the reinforced concrete columns. In this study, an adaptive method for assessing the reliability of columns with respect to damage states is proposed. The method is an indirect coupling of the response surface and finite element model in the non-linear domain. The main goal of this study was to provide a structural engineer with a modelling approach for optimal and robust column design. The results of the present study show that the reliability of columns belonging to portal frames is closely related to the quality of the constituent materials (steel and concrete) and the type of load applied. The reliability of this type of column also decreases with increasing load and applied displacement and increases with increasing compressive strength and yield strength of the steel. The uncertainties associated with the structural models are considered, with their impact on structure reliability studied using a sensitivity analysis, which allows the proposed approach to make the best possible decision for a better design and, therefore, good behaviour under different parameters.

Key words:
uncertainties, reliability, probabilistic methods, damage, column, portal

Prethodno priopćenje

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Učinci oštećenja stupova na pouzdanost armiranobetonskih okvirnih nosača

Pouzdanost i ponašanje stupova armiranobetonskih okvirnih nosača ovise o mnogim čimbenicima. U radu je opisana parametarska analiza pouzdanosti stupa u nelinearnom području za kritična područja oštećenja armiranobetonskih stupova, pri čemu je u obzir uzeta mehanička varijabilnost. U ovom radu predložena je adaptivna metoda za procjenu pouzdanosti stupova s obzirom na stanja oštećenja. Metoda je neizravno uparivanje odzivne površine i nelinearnoga modela konačnih elemenata. Glavni je cilj ovog istraživanja pružiti građevinskim inženjerima model za optimalno i robusno oblikovanje stupova. Rezultati studije pokazuju da je pouzdanost stupova okvirnih nosača usko povezana s dobrom kvalitetom materijala (čelik, beton) i vrstom primijenjenog opterećenja. Njihova pouzdanost opada s povećanjem opterećenja i nanesenoga pomaka, a raste s povećanjem tlačne čvrstoće i granice razvlačenja čelika. U predloženom pristupu uzimaju se u obzir nesigurnosti povezane s konstrukcijskim modelima i proučava se njihov utjecaj na pouzdanost konstrukcije pomoću analize osjetljivosti, a sve s ciljem ostvarivanja bolje oblikovanosti i posljedično boljega ponašanja stupova pod različitim parametrima.

Ključne riječi:
nesigurnosti, pouzdanost, probabilističke metode, oštećenje, stup, nosač

1. Introduction

Civil engineering structures are exposed to unavoidable risks such as earthquakes, making some elements, such as columns, prone to failure. In the case of load levels close to the damage, reinforced concrete columns automatically exhibit non-linear behaviour. The design of reinforced concrete columns is an axis of research that has received much attention in recent years. Several experimental [1-4] and numerical studies on reinforced concrete portal frame elements [5-11] have been conducted to explore the behaviour of portal frame elements.

Alfarah et al. [10] presented a new methodology for calculating the evolution of the damage variables on two portal frames. The results obtained were also compared with simplified models commonly used in earthquake engineering.

Haji et al. [12] conducted an experimental study on the impact of FRP strengthening techniques, but the problem of reinforced concrete columns is still relevant because these columns no longer meet the requirements of the design codes. They showed a particular mode of failure during recent seismic events.

Non-linear analyses of concrete columns are used as a research tool to improve the understanding of structural behaviour and are also useful for designing and estimating the level of reliability. Therefore, a probabilistic approach to non-linear analysis is of great practical interest to structural engineers. Considering uncertainties in the mechanical modelling of structures is an indispensable condition for an optimal and robust design of their reliability. The effect of uncertainties must be assessed to determine the reliability of Morio et al. 's structural system [13]. The main consideration in the reliability analysis of structures is to consider the uncertainties in the damage stage using a predefined limit state function. This function is obtained using the response surface method (RSM) by fitting a surface to various realisations for a set of variables [14-15]. With this objective, reliability methods have been developed for several years by different researchers [16-22] to study the behaviour of structural elements. Non-linear models can be used to clearly represent the damage states of structural elements where structural reliability analysis is of interest. These methods make it possible to study the reliability of structures and the influence of the variability of design variables on their behaviour [19].

Mechanic-reliability coupling methods must consider the consequent resolution difficulties (such as large number of random variables and non-linear behaviour) to make reliability studies efficient and exploitable [20, 21].

Molkens et al. [20] described the system-level behaviour of portal frames based on an analytical reliability approach with dominant failure modes. Structural reliability methods have been developed significantly in recent years and are considered a useful tool for efficiently assessing the safety of structures with complex designs Gordini et al. [23]).

This research aimed to evaluate the reliability of columns belonging to reinforced concrete frame portals, considering the criterion collapse using a probabilistic non-linear dynamic analysis. In this study, a targeted reliability study of columns (base and nodal zone) was proposed, and a relationship between the structural reliability index and the damage factors was established using a sensitivity study. A reliability study of the portal frame columns can be used as a decision-making tool for a possible inspection and rehabilitation plan.

2. Methodology

2.1. Damage theory

Based on the damage theory to the post-elastic behaviour of concrete, an internal variable D (scalar or tensor) takes values from zero (0) (undamaged material) to the value of (1) (material totally damaged). For example, in the scalar case,

$$D = 1 - \frac{\bar{E}}{E} \tag{1}$$

where:

E - Young modulus of the material in the initial state

Ē - Young modulus of the damaged material.

The evolution of D is determined deductively from the measurements of the variation of the apparent module, reported to the initial state of the material considered intact, leading to the notion of effective stresses in damage, as initially proposed by Chaboche et al. [24].

The degraded response of concrete is characterised by two independent uniaxial damage variables: tensile damage D_T and compressive damage D_C.

$$0 \leq D_T \leq 1 \text{ i } 0 \leq D_C \leq 1 \tag{2}$$

2.2. Basic theory of structural reliability

In reliability-based topology optimisation, it is assumed that the limited state function corresponding to the failure mode of a structural element contains m basic stochastic variables Xi, i= 1 ,..., m. These variables were used to model the yield strength and loads.

For structural elements, the performance function is given by Eq. (3)

$$G(x) = R - S \tag{3}$$

where:

R - resistance of the structure

S - stress imposed on the structure.

In the physical space formed by *R* and *S*, the limit state function divides the physical space into three domains: $G(R, S) < 0$ failure domain, $G(R, S) = 0$ limit state and $G(R, S) > 0$ safe domain.
In this study, the first-order reliability method (First Order Reliability Method) and second-order reliability method (SORM) were used.

a) FORM method
This method is based on an approximation of the limit state function using a hyperplane at the design point PC, as shown in Figure 1 [25]. In the standardised space, the probability of failure is expressed as

$$P_f = \int_{g(\bar{x})\leq 0} f_{\bar{X}}(\bar{x})\,d\bar{x} \tag{4}$$

Where $f_x(\bar{x})$ is the density function of $\bar{X}$. The probability of failure is defined as $P_f = \theta\ (-\beta)$, where θ is the standard normal cumulative function.

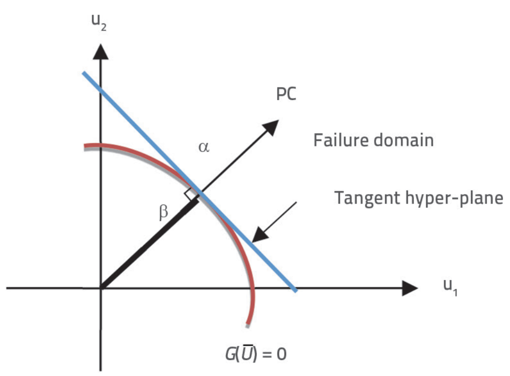

Figure 1. Approximation by a tangent hyperplane - FORM method [25]

b) SORM method
The SORM method [26] approximates the limit state function using a homogeneous or inhomogeneous quadratic form at the design point, PC. This probability was corrected to better account for the curvature of the limit state Figure 2. The probability of failure is estimated by

$$P_f = \phi(-\beta)\Pi_{i=1}^{n-1} n \frac{1}{\sqrt{1+\beta k_i}} \tag{5}$$

The reliability index was calculated as the shortest distance between the origin and the failure surface, where $\bar{u}$ - space:

$$\beta = \min_{g\left(T^{-1}(u)\right)=0} \left(\sum_{i=1}^{m} u_i^2\right)^{½} \tag{6}$$

A reliability index β for the series system can be defined as:

$$\beta = \phi^{-1}\,(P_f) \tag{7}$$

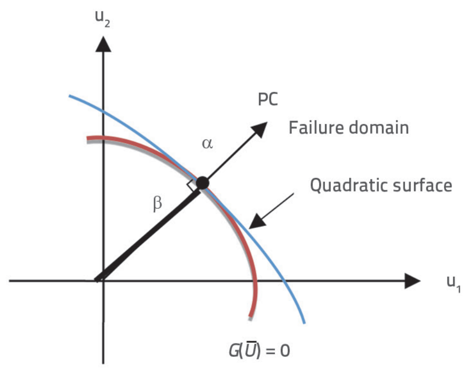

Figure 2. Approximation by a tangent hyperplane - SORM method [26]

2.3. Mechanic-reliability coupling algorithm

Numerical simulations of physical phenomena have become essential in several areas of contemporary science. In general, these models provide predictive results only if the input parameters provided are estimated well. In most cases, these parameters are difficult to measure or intrinsically variable from one system to another. Therefore, it is necessary to describe these uncertainties in a suitable framework and study their influence on mechanical behaviour. To do this, probabilistic mechanics has developed an arsenal of methods to assess the probability of a load exceeding the strength of the structure, especially when a finite-element solution is used; it is a communication or dialogue between a finite element calculation code and reliability algorithm. Mechanic-reliability coupling requires data concerning the reliability model (random variables, distribution laws, coefficient of variation, and the parameters of the reliability resolution algorithm) and the numerical model for calculating the performance function. The model built using the finite element method is associated with an interface that allows it to be driven by a reliability algorithm. In other words, the algorithm sends a set of parameters to the model and receives a deterministic estimate of the corresponding performance function and its gradients in return. In this study, coupling with ABAQUS [27] finite element code and MATLAB code was used [28]. The method chosen to achieve this coupling was indirect coupling by the response surface [29]. A flowchart of the mechanical–reliability coupling (ABAQUS-MATLAB) is shown in Figure 3.

2.4. Validation of the analysis model

This study evaluates the performance and behaviour of columns belonging to single- and two-story reinforced concrete frames under horizontal displacement. To compare the results, the choice was made to use the experimental and numerical results of Faleiro et al. [1], Valipour et al. [7], Vukić et al. [8], Del Vecchio et al. [9] and Alfarah et al. [10]. Figure 4 presents the geometry and reinforcement of

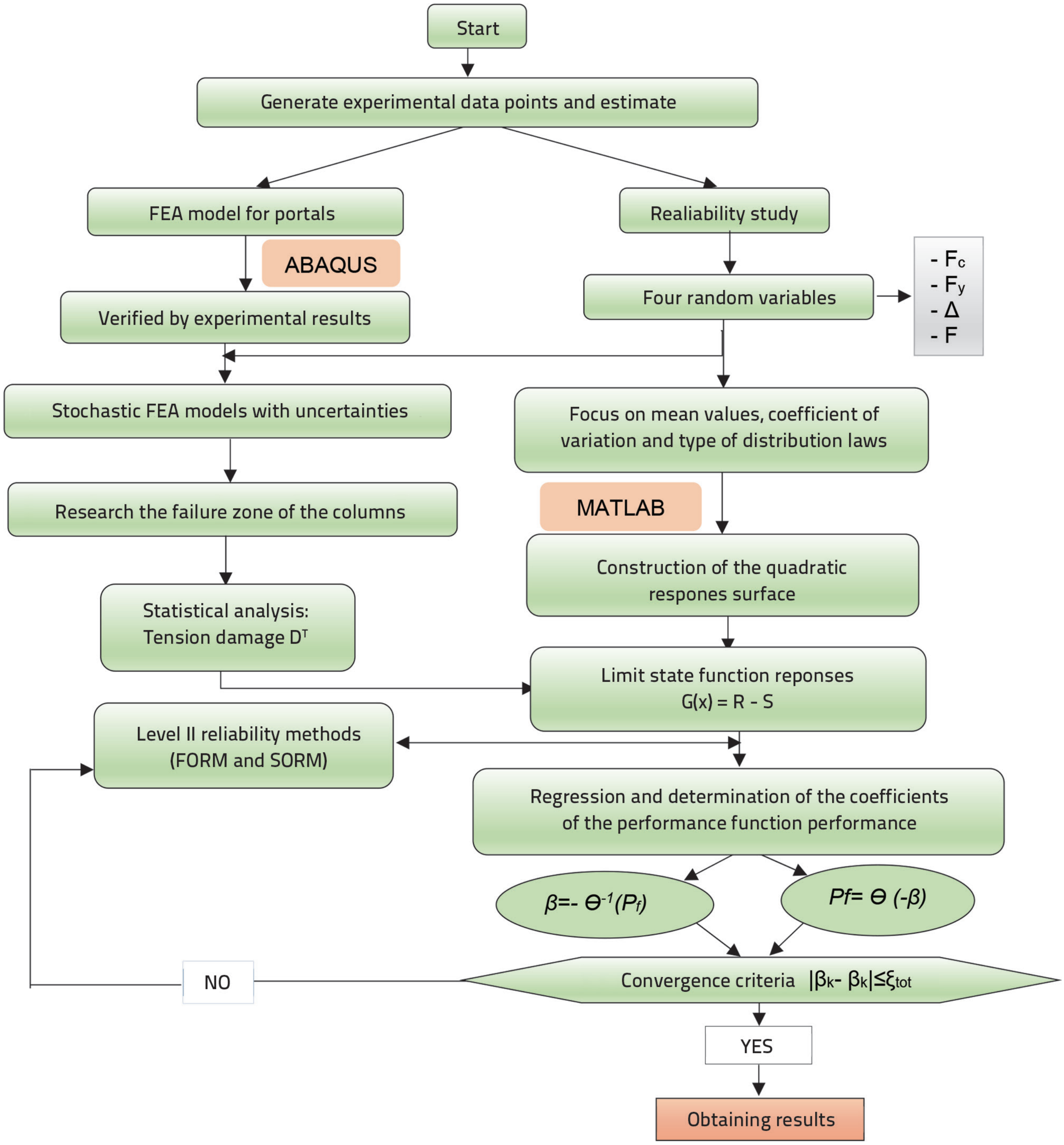

Figure 3. Flow chart of a mechanical-reliability coupling (ABAQUS-MATLAB)

the experimental model of the double-story portal frame in millimetres. Figure 4(a) and (b) show the front and side views of the tested frame, respectively. Figure 4(c,d) shows the cross-sections of columns and beams, respectively, where the columns and beams have the same cross-section b h = 300 x 400 mm; all frame members were similarly reinforced with four Ø20 deformed bars as the bottom as the top, and Ø10 closed stirrup reinforcement at 125 mm spacing as shear reinforcement. Figure 4 shows the left top of the frame at a constant vertical force of 700 kN that acts at the top of both columns and the monotonic displacement to the top left joint [10].

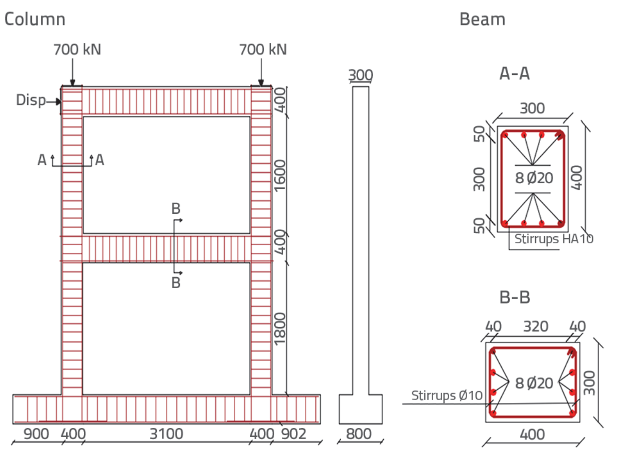

Figure 4. Geometrical view of two-storey portal, sections, reinforcing details and loading [10]

The geometry and reinforcement of the single-story portal proposed in this research are shown in Figure 5 with a height of 2.2 m.

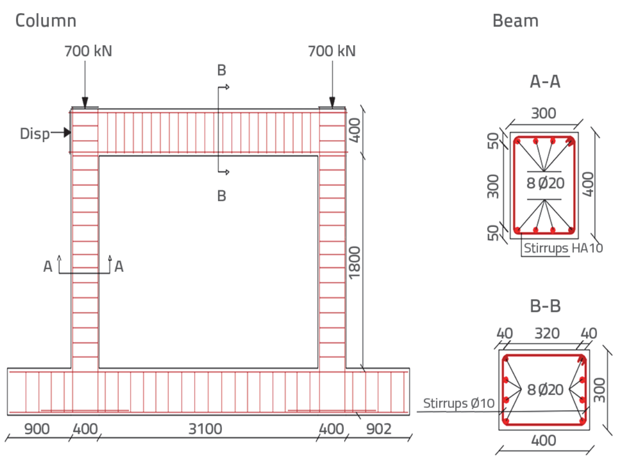

Figure 5. Geometrical view of single-storey portal, sections, reinforcing details and loading

The mechanical parameters of the materials used are listed in Table 1, according to Alfarah et al.[10].

Table1. Mechanical parameters of the materials: concrete and steel

Parameters / Materials	F_c [MPa]	F_t [MPa]	E [MPa]	ν
Concrete	30	2.912	26000	0.2
Steel	F_y [MPa]	F_u [MPa]	E_s [MPa]	ν
Ø20	418	596	192500	0.3
Ø10	454	640	200000	0.3

2.5. Finite element analysis modelling

The use of non-linear behaviour models is still relatively rare in the industry. Numerical models can improve the representation of parts or structural elements. Numerical simulations based on the ABAQUS (2012) finite element code were performed on portals under a monotonic horizontal load of seismic type. The results of the simulations were validated by contributing to the results of the simulations tested in [1, 7-10]. In this paper, concrete behaviour is simulated with "Concrete Damaged Plasticity" [7] integrated into the finite element code ABAQUS [22]. It is a coupled model (plasticity, damage) based on damage, including irreversible deformations, and is mainly intended for the general analysis of concrete structures under cyclic and/or dynamic loading. Steel exhibits elastic–plastic behaviour with compression and tension hardening. These models are particularly well-suited for reproducing failure modes based on tension cracking and compression crushing [10]. Embedded region contact was employed for concrete and steel, with the mesh size chosen according to Alfarah et al. [10]] (for concrete 100 mm, for steel 25 mm) and an embedding marked on the sole of the portal.

2.6. Comparative study of the mechanical behaviour of columns

A comparative study of the mechanical behaviour of two portal cases (single-story portal and two-story portal) in terms of resistance. Figure 6 shows the experimental results plotted along with the numerical results obtained for the two portal cases. The curves are very close to each other. The value of the maximum force obtained by the experimental study was 332 kN [1, 7-10] and that for the simulated portal was 324 kN with a horizontal displacement of 150 mm, showing the approach of the numerical results obtained and the calibration of the proposed model. For the proposed single-story portal, an increase in force to 456 kN compared to the double-story portal shows a good strength capacity of the latter.

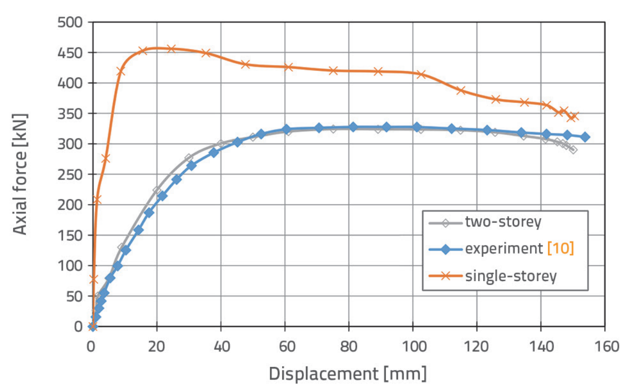

Figure 6. Axial force vs. displacement of the three types of portals

According to the experimental test of Faleiro et al. [1], the first flexural cracks were observed at 52.5 kN in the first-story beam at the north bottom face and south top face. At a load of 145 KN, flexural cracking occurred at the base of the columns, and the first web-shear in the first-story beam was detected.

The first yielding occurred in the bottom reinforcement north of the first-story beam at a load of 264 kN, but in the top reinforcement at the south end of the beam after a load of 287 kN. Yielding at the base of both columns and hinging at both ends of the first-story beam occurred when the load approached 323 kN. Concrete crushing and hinging were evident at the base of the columns shortly after at a load of 329 kN. The frame sustained an ultimate lateral load of 332 kN, at a lateral displacement of approximately 150 mm.

2.7. Tensile damage distribution

The distribution of tensile damage on the single- and double-story talks is shown in Figure 7 and Figure 8. The red colour represents maximum damage and the blue colour represents minimum damage. It can be observed that the distribution of the maximum damage on the columns is concentrated at the three selected points in Figure 7 and figure 8. This comparative study is limited to the three selected points in the critical zones of columns P01 (left column base), P02 (Right column base) and

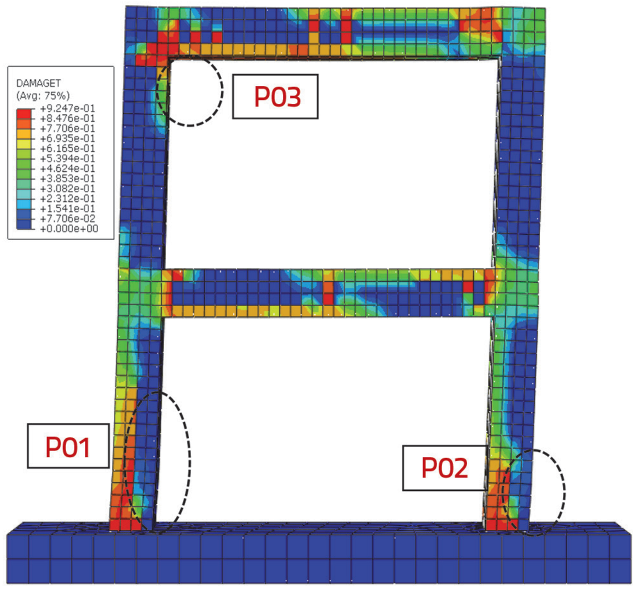

Figure 7. Damaged double-storey portal

Table 2. Results of the finite element simulations

Specimen	F_c [MPa]	F_y [MPa]	Δ [mm]	F [kN]	Two-storey frame			Single-storey frame		
					P01	P02	P03	P01	P02	P03
01	30	418	150	700	0.914	0.826	0.779	0.8793	0.837	0.5575
02	30	427	148	705	0.907	0.846	0.801	0.879	0.823	0.62
03	30	409	153	698	0.9017	0.868	0.773	0.878	0.85	0.619
04	30	436	155	696	0.9002	0.889	0.865	0.88	0.884	0.635
05	30	418	150	705	0.912	0.848	0.803	0.877	0.858	0.618
06	28.5	427	155	700	0.9019	0.900	0.775	0.874	0.827	0.626
07	28.5	409	148	698	0.883	0.9013	0.78	0.872	0.864	0.695
08	28.5	436	153	696	0.903	0.865	0.803	0.873	0.847	0.624
09	28.5	418	155	705	0.89	0.886	0.9247	0.87	0.792	0.583
10	28.5	427	150	698	0.88	0.924	0.916	0.875	0.811	0.713
11	31.5	409	155	700	0.9014	0.849	0.76	0.885	0.851	0.631
12	31.5	436	148	705	0.89	0.863	0.884	0.884	0.902	0.574
13	31.5	418	153	700	0.909	0.919	0.796	0.881	0.887	0.614
14	31.5	427	153	696	0.906	0.852	0.794	0.883	0.897	0.627
15	31.5	409	150	698	0.908	0.87	0.777	0.882	0.815	0.612
16	33	418	148	700	0.898	0.924	0.782	0.891	0.884	0.595
17	33	427	155	705	0.904	0.925	0.768	0.89	0.914	0.588
18	33	436	150	700	0.903	0.888	0.87	0.887	0.917	0.579
19	33	436	148	696	0.901	0.923	0.848	0.885	0.912	0.63
20	33	407	153	698	0.912	0.894	0.881	0.886	0.895	0.624
21	28.5	418	150	700	0.897	0.881	0.787	0.871	0.852	0.6
22	31.5	418	150	705	0.913	0.908	0.781	0.88	0.902	0.606
23	33	418	148	696	0.902	0.916	0.8	0.885	0.835	0.602
24	30	418	155	705	0.888	0.854	0.793	0.877	0.839	0.566
25	33	436	155	705	0.9	0.924	0.801	0.888	0.91	0.543

P03 (Top left column), and according to Alfarah et al. [10], the maximum tensile damage value is 0.9247.

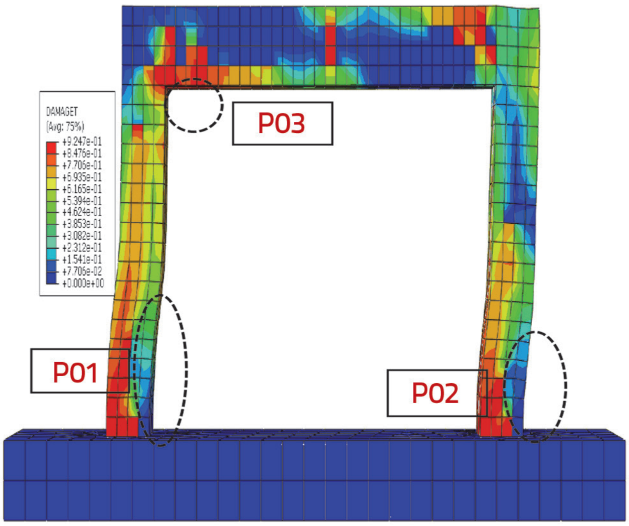

Figure 8. Damaged single-storey portal

3. Results, discussion and analyses

3.1. Reliability study

Several simulations were performed to initiate the reliability analysis of columns belonging to two types of portals (single-story portal and two-story portal). In this study, four random variables were considered. Twenty-five simulations were performed on this type of column to construct a reduced centred composite design ($2^4 + 2 \times 4 + 1 = 25$). The random variables of the probabilistic model are concrete compressive strength F_c(28.5, 30, 31.5, and 33 MPa), steel yield strength F_y (409, 418, 427, and 436 MPa), horizontal displacement Δ (148, 150, 153, and 155 mm), and axial force F (696, 698, 700, and 705 kN).

Twenty-five simulation models were modelled by ABAQUS (2012). To obtain the different values of the tensile damage D_T for the three points of the selected portal, they were then compared to the maximum damage value (1). Table 2 presents the results obtained from the simulations for each point of the two types of portals.

Table 2 shows that the tensile damage values D_T of point P01 (left base column) are higher compared to the other points P02 and P03, which confirms the large cracks marked in point P01 according to Alfarah et al. [10].

The mean value and coefficient of variation (COV) parameters of the random variables (concrete compressive strength Fc, steel yield strength Fy, horizontal displacement, and axial force F) were taken from references [22, 34, 35] and are listed in Table 3.

3.1.1. Formulation of the limit state function G(x)

The limit state function used in this study was defined according to Eq. (8).

$$G(x) = 1 - D_T(F_c, F_y, \Delta, F) \tag{8}$$

where $D_T(F_c, F_y, \Delta, F)$ fresponse function obtained by quadratic regression of the numerical finite element results obtained using MATLAB.

3.1.2. Reliability index and probability of failure

The results of the reliability index and the probability of failure of the three points of columns belonging to the two types of portalare are summarised in Table 4. The reliability index β and failure probability ρf calculated by the two methods, FORM and SORM, were very close for each study.

Table 3. Statistical characteristics of the random variables

Variables	Distribution	Mean value	COV	Reference
F_c	Normalno	30.75 [MPa]	0.19	Jiang et al. [16]
F_y	Log-normalno	422.5 [MPa]	0.045	Thai et al. [30]
Δ	Normalno	151.5 [mm]	0.1	Rahman et al. [31]
F	Gumbel	699.5 [kN]	0.25	Beck et al. [32]

Table 4. Results of the reliability study

Method	Reliability	Two-storey frame			Single-storey frame		
			P02	P03	P01	P02	P03
FORM	β	0.92	1.603	2.944	1.664	1.889	3.641
	ρf	0.46	5.44E-02	1.62E-03	4.81E-02	2.95E-02	1.36E-04
SORM	β	0.975	1.477	2.963	1.662	1.924	3.668
	ρf	0.16	6.99E-02	1.52E-03	4.82E-02	2.72E-02	1.22E-04

For the three damaged columns of the two-story portal, the value reliability index varied from 0,92 to 2,944 using the FORM method and from 0,975 to 2,963 using the SORM method; for the three damaged columns of the single-story portal, the value reliability index varied from 1,664 to 3,641 using the FORM method and from 1.662 to 2,963 using the SORM method; the probability of failure decreases as the reliability index of each point increases, indicating that the value of the reliability index of P01 (left column base) is smaller compared to the other column points for the two types of portals, which confirms the results of Table 4 by the large cracks marked in point P01 [10]. Conversely, the reliability index of point P02 was higher, which indicates the reliability of the latter.

3.2. The influence of random variable on the reliability of columns

To evaluate the influence of random variables on the reliability of the columns, a parametric study was conducted. Hence, a variety of random variables and conservation of the values of the others have been carried out, and two cases are presented.

3.2.1. Concrete compressive strength (Fc)

The analysis of the behaviour of columns belonging to the two types of portals under the effect of the concrete compressive strength is illustrated in Figure 9.

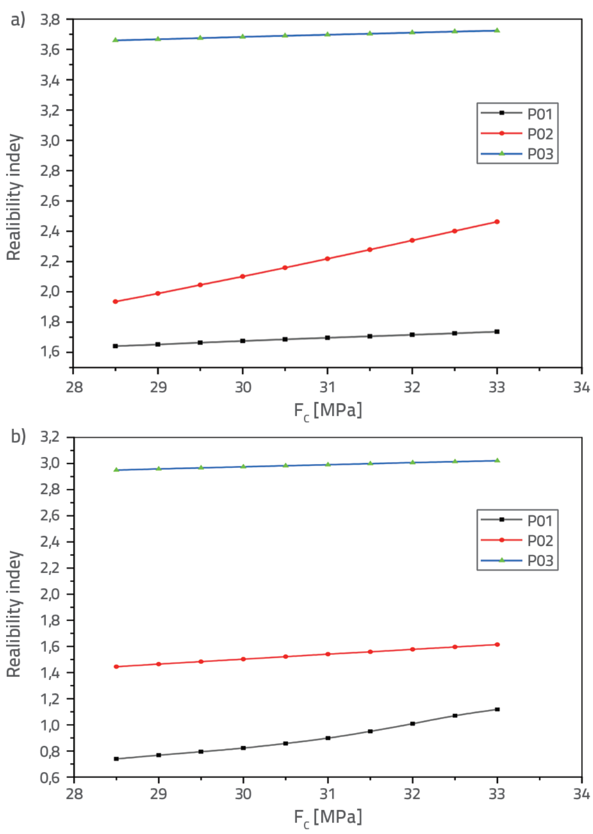

Figure 9. Effect of concrete compressive strength: a) Single-storey portal; b) Two-storey portal

The results show that the reliability index increases with increasing concrete compressive strength (F_c) for both types of portal frames. For the single-story portal columns shown in Fig. 9. (a), the value of the reliability index varied from 1.641 to 1.736 for point P01, 1,935 to 2,462 for point P02 and for point P03 from 3,66 to 3,724. For the column points belonging to the two-storey portal Fig.9.b, the value of the reliability index varied from 0.7393 to 1,118 for point P01, from 1,445 to 1,614 for point P02 and for point P03 from 2.95 to 3,022.

3.2.2. Steel yield strength

According to the results in Figure 10, the reliability index increased with an increase in the steel yield strength random variable for points P01 and P03 for the two types of portal frames. For point P03, the values of the reliability index are identical and are equal to 1.9 and 1.5, respectively Figure 10. (a, b).

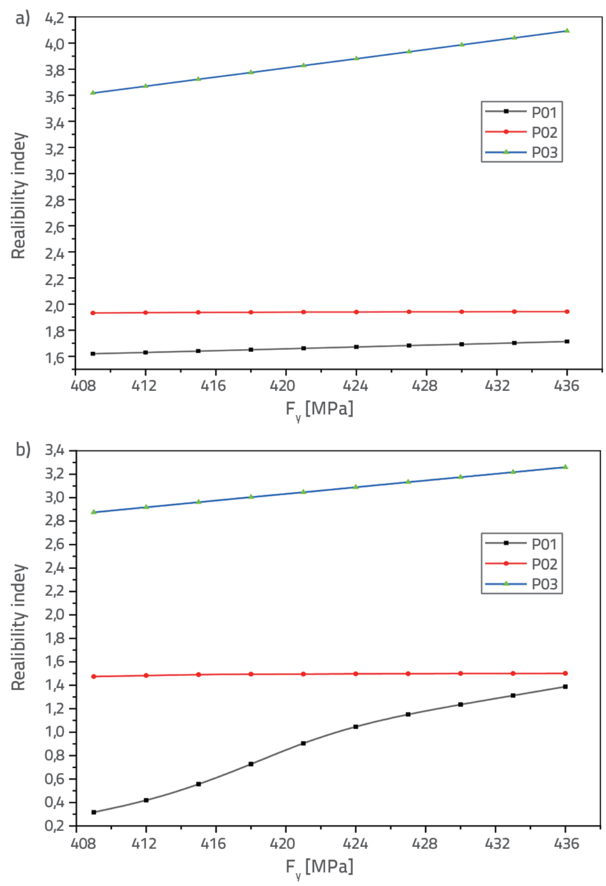

Figure 10. Effect of steel yield strength: a) single-storey portal; b) Two-storey portal

3.2.3. Horizontal displacement

The results are shown in Figure 11. (a) shows a slight decrease in the reliability index values with increasing applied displacement for all points (P01, P02, P03) of the single-story portal columns. For points P02 and P03, the values of the reliability index were equal. Based on the results in Figure 11. (b), the values of the reliability index decrease with increasing applied displacement for points P01 and P03 of the two-story portal columns. For P03, the values are identical.

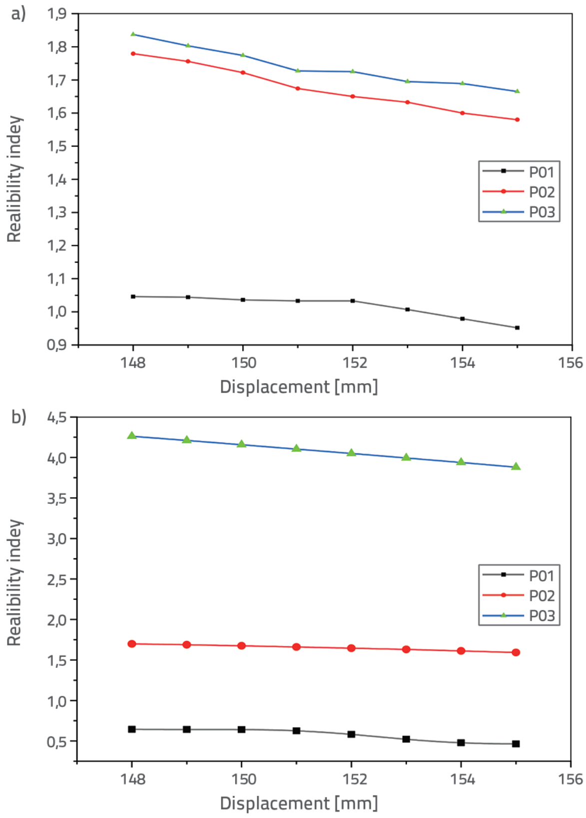

Figure 11. Effect of Horizontal displacement: a) Single-storey portal; b) Two-storey portal

3.2.3. Axial force

The variation in the reliability index as a function of the axial force applied to the top of the columns is shown in Figure 12. A slight decrease in the values of the reliability index as a function of increasing applied axial forces for all points (P01, P02, P03) of the two types of portals (single-story portal and two-story portal), as indicated in Figure 12.

The results of Figures 9 to 12 give important observations. The reliability index values for the three points of the single-deck portal columns are higher compared to those of two-storey portal, which indicates the reliability of the single-deck portal columns. The minimum values of the reliability index in this comparative study are observed in the two variables the horizontal displacement (Δ) and the axial force (F) [33] in point P01 (left column base) [10], which shows the impact and importance of these variables. According to the reliability index values obtained in Figure 10, the displacement variable had the same influence on points P02 and P03 of the single-story portal column.

The study of the influence of random variables on the reliability of the columns confirms the results shown in Table 2 and the results of Alfarah et al.[10].

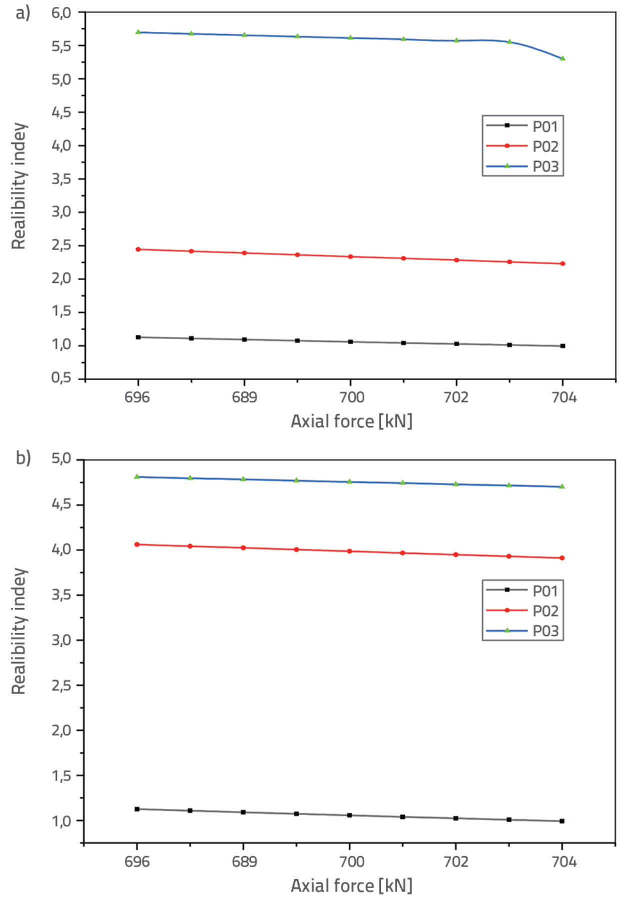

Figure 12. Effect of Horizontal displacement: a) Single-storey portal; b) Two-storey portal

3.3. Sensitivity analysis

Sensitivity analysis is an essential step in determining the quality of the results, and the objective of this study is to determine the most important variables to better control them in the decision-making stage in the case of several variables [19]. The sensitivities of the random variables of the single- and two-story portal columns are summarised in Figure 13 and Figure 14.

The results in Figure 12 show that the most influential parameters on the behaviour of columns belonging to a single-story portal frame are the axial force applied to the columns with percentages of 48 % for point P01, 28 % for P02, and 30 % for P03, and the horizontal displacement (Δ) with percentages of 24 % for point P01, 34 % for P02, and 40 % for P03. However, the sensitivity of the parameters, concrete compressive strength, and steel yield strength also play a role in safety. According to the results obtained in Figure 13, the percentages of the axial force variable applied to the columns were very high at 56 % on P01, and for the displacement (Δ) with a percentage of 36 % marked at point P03. Nevertheless, it can be said that all the parameters work together for the good behaviour of columns belonging to portals with different storeys. The results in Figure 13 and Figure 14 confirm the results obtained in the study on the influence of random variables on the reliability of the columns.

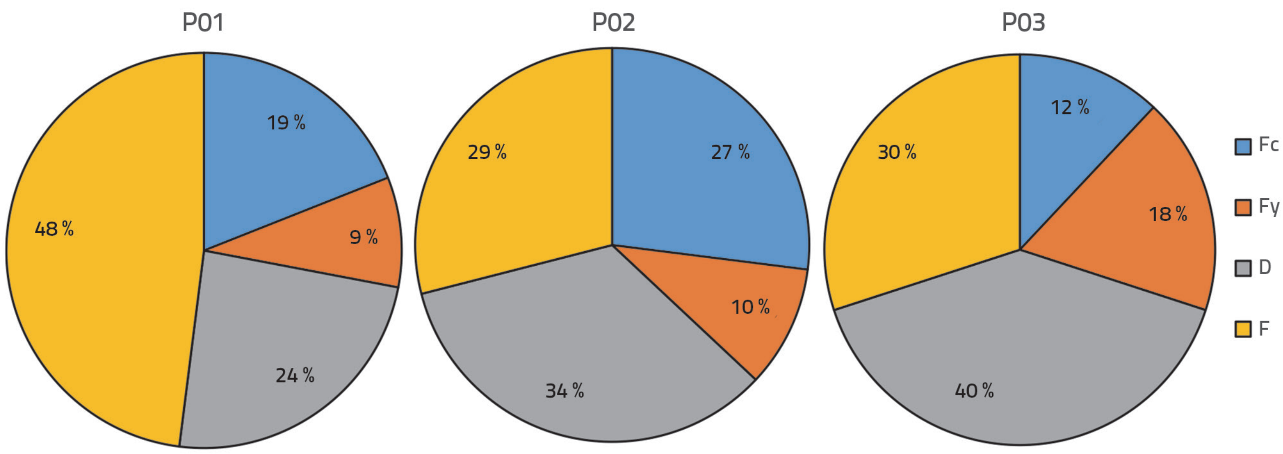

Figure 13. Sensitivity of parameters for single-storey portal

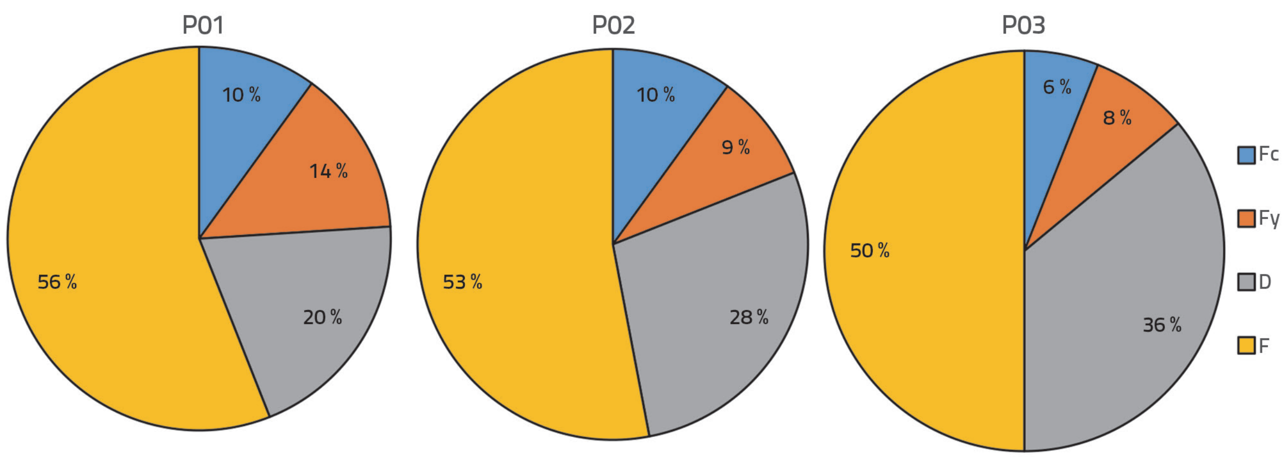

Figure 14. Sensitivity of parameters for two-storey portal

4. Conclusion

In the proposed model, the influence of some parameters on the reliability of different points of damaged columns belonging to different story portals is subjected to horizontal displacement. A mechanical reliability (ABAQUS-MATLAB) model was applied to assess the reliability of the columns in the damage domain, which proved to be very robust in analysing the performance of the columns of the different story portals (single and two-story). The results obtained in this comparative study on the reliability of the most damaged points on columns belonging to single- and two-story portals under horizontal displacement necessitated the listing of important conclusions.

The single-story portal represents a high resistance compared to the two-story portal under the same displacement, with a gain in strength of approximately 41 %.

The reliability study determined and compared the evolution of the reliability index of the damaged points on the different story portal columns considering the variability of some parameters, material damage, and applied loading. The study of the influence of random variables on the reliability of the columns and the sensitivity analysis revealed that the most important parameters affecting the behaviour of the columns were the axial force applied to the columns and the horizontal displacement applied to the portal frame, without neglecting the contribution of other parameters.

The mechanical study of the RC frame is confirmed by a reliability study using a mechanic-reliability coupling to present a decision support tool for design engineers to deal with the variability of mechanical and geometrical parameters of structural elements. Furthermore, as a guideline for future researchers and for greater flexibility in decision-making, it is sufficient to use the proposed approach with a multivariate parametric study. This approach is particularly suitable for the possible implementation of geometric and material nonlinearities with various analyses (static, dynamic, and non-linear), considering uncertainties arising from material and geometric characteristics.

Future research should be conducted to provide a better understanding of structural element reliability

- investigate the effects of concrete-steel interactions
- develop a reliability method for RC frames
- study the reliability of RC beam–column joints.

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