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PREDICTION OF THE PERFORMANCE OF REINFORCED CONCRETE ELEMENTS UNDER MONOTONIC AND CYCLIC LATERAL LOADING

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Abstract
Introduction: The nonlinear behavior of reinforced concrete elements under monotonic and cyclic loading is one of the most important research topics in seismic regions. Over the past 30 years, several experimental investigations have been conducted with the aim of better understanding the behavior of reinforced concrete elements and determining the various parameters influencing this behavior. **Purpose of the study:** The present research investigates this behavior and aims to develop an interactive computer program designed for use within the Windows environment. **Methods:** Several material models (confined/unconfined concrete and reinforcing steel), as well as hysteresis laws, are employed in an analytical approach using the fiber element. For each specimen, geometric characteristics, material models, plastic hinge locations, axial loads, and the history of corresponding horizontal displacements were input into the program. Numerical predictions are validated against experimental results from diverse studies. **Results:** Convergence analysis using experimental data demonstrated good agreement between numerical and experimental results, particularly in hysteresis behavior, force-displacement envelope curves, maximum strength, initial stiffness, stiffness degradation, and cumulative energy dissipation. The findings underscore the efficacy of the developed program in accurately predicting the nonlinear behavior of reinforced concrete elements. The developed program provides a reliable tool for predicting the nonlinear behavior of reinforced concrete elements under cyclic loading, validated through convergence analysis with experimental data.

Keywords: computer program, fiber element, hysteresis, materials models, moment-curvature.

Introduction

Performance-based design is a methodology aimed at achieving predictable behavior of a structure and its elements during an earthquake (Djebbar, 2006; Esmaeily and Peterman, 2007). This prediction of damage evolution requires a realistic assessment of the performance and behavior of different structural elements (Chadwell and Imbsen, 2004; Sato et al., 2002). The failure of these elements in a precise chronological order and at targeted locations (fuse element) will cause progressive structural failure.

The behavior of reinforced concrete columns is considered to be a very important research topic in seismic-prone areas (Nawy, 1996; Rodrigues et al., 2013b). The nonlinear behavior of reinforced concrete columns has been the subject of several experimental studies (Rodrigues et al., 2013b; Shirmohammadi and Esmaeily, 2015). The behavior depends on the level of the applied axial load, the history of lateral loading, geometric characteristics of the cross section, properties of the materials (concrete and reinforcing steel), density, and the configuration of longitudinal and transverse reinforcement (Abd El Fattah, 2012; Furtado et al., 2015; Rodrigues et al., 2013a, 2014; Shirmohammadi, 2015; Shirmohammadi and Esmaeily, 2015). Evaluating one or more of these parameters is costly. Therefore, numerical simulation becomes an unavoidable alternative for conducting possible parametric studies on the behavior of reinforced concrete columns under cyclic loading (Shirmohammadi and Esmaeily, 2015).

Most available analysis tools are limited to analysis under monotonic loading and are difficult for engineers to use. Engineers prefer easy analytical approaches with satisfactory accuracy (Esmaeily and Peterman, 2007).

The main objective of the present study is to develop an interactive computer program that is easy to use in the Windows environment and capable of predicting the behavior of reinforced concrete elements under both monotonic and cyclic loading with acceptable precision. The second part of the study is dedicated to validating the program by comparing the numerical results with those of tests conducted by various authors.

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Development of the computer program for analysis

Basis of analysis

The analysis is based on the fiber element, which is widely used by several researchers and software (Esmaeily and Peterman, 2007). In this analysis, the concrete cross section is divided into a number of rectangular finite elements called fibers (Fig. 1). The reinforcing steel bars are not meshed due to their small surface areas. Each fiber of the cross section is associated with a set of data: coordinates (Y, Z), surface area, and material type identifier (confined/unconfined concrete and reinforcing steel) (Sato et al., 2002).

The geometry of the cross section, the mesh size, the quantity, and the configuration of reinforcing steel (Fig. 2), as well as the models and material hysteresis laws (Fig. 3), can be defined or selected by the user through the graphical user interface (GUI).

The axial load, the plastic length model (Fig. 4), and the monotonic or cyclic displacement (Fig. 5) serve as input data for controlled displacement analysis. This approach captures the state of strain, stress, force, and moment of each fiber section. The history of each fiber is archived, traced, and updated at each step of the analysis (Chadwell and Imbsen, 2004; Esmaeily and Peterman, 2007; Sato et al., 2002).

Material models (concrete and steel)

Interface presentation

For the stress-strain material relationship, multiple material models and hysteresis laws are provided (Fig. 3), which can be selected and customized depending on the user's choice and analysis needs. Tensile strength is not considered in any of the concrete models (confined and unconfined). In the case of reinforced concrete, three material models and hysteresis laws must be defined (reinforcing steel, confined concrete, and unconfined concrete).

Monotonic unconfined concrete models

Seven unconfined concrete models (Fig. 3) can be selected and configured based on user preferences. These models include Popovics 1973 (Lee, 2017; Popovics, 1973), Mander 1988 (Mander, 1983, Mander et al., 1988), Kent & Park 1971 (Kent, 1969; Kent and Park, 1971; Lee, 2017; Park and Paulay, 1991; Park et al., 1982; Scott, 1980), Hognestad 1951 (Hognestad, 1951; Lee, 2017; Scott, 1980), Carreira & Chu 1985 (Carreira and Chu, 1985), Tsai 1988 (Tsai, 1988), Desayi & Krisnan 1964 (Desayi and Krishnan, 1964). These models can be adjusted according to specific requirements (modulus of elasticity, yield stress, yield strain, ultimate strain), offering a wide variety for unconfined concrete.

Monotonic confined concrete models

The user has four choices (Fig. 3): three confined concrete models Mander 1988 (Mander, 1983, Mander et al., 1988), Kent & Park 1971 (Kent, 1969; Kent and Park, 1971; Lee, 2017; Park and Paulay, 1991; Park et al., 1982; Scott, 1980), Cusson & Paultre 1994 (Cusson and Paultre, 1994, 1995) and a fourth option obtained by selecting the fourth checkbox, indicating the exclusion of the confinement effect.

Confined and unconfined concrete hysteresis law

A single linear elastic hysteresis law is employed for all concrete models, whether confined or unconfined, because of its simplicity to program.

Monotonic and cyclic models of reinforcing steels

To simulate the behavior of longitudinal steel bars, three models were incorporated (Fig. 3): the elasto-plastic model (Li, 2004), the Giuffrè–Menegotto–Pinto model (Bosco et al., 2016; Carreño et al., 2020; Menegotto and Pinto, 1973; opensees.berkeley.edu, 2023), and the Esmaeily

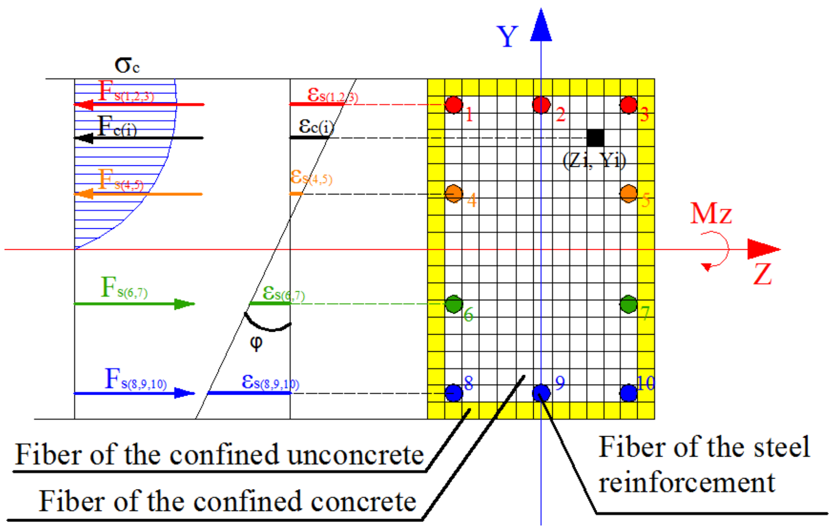

Fig. 1. Discretization of reinforced-concrete sections

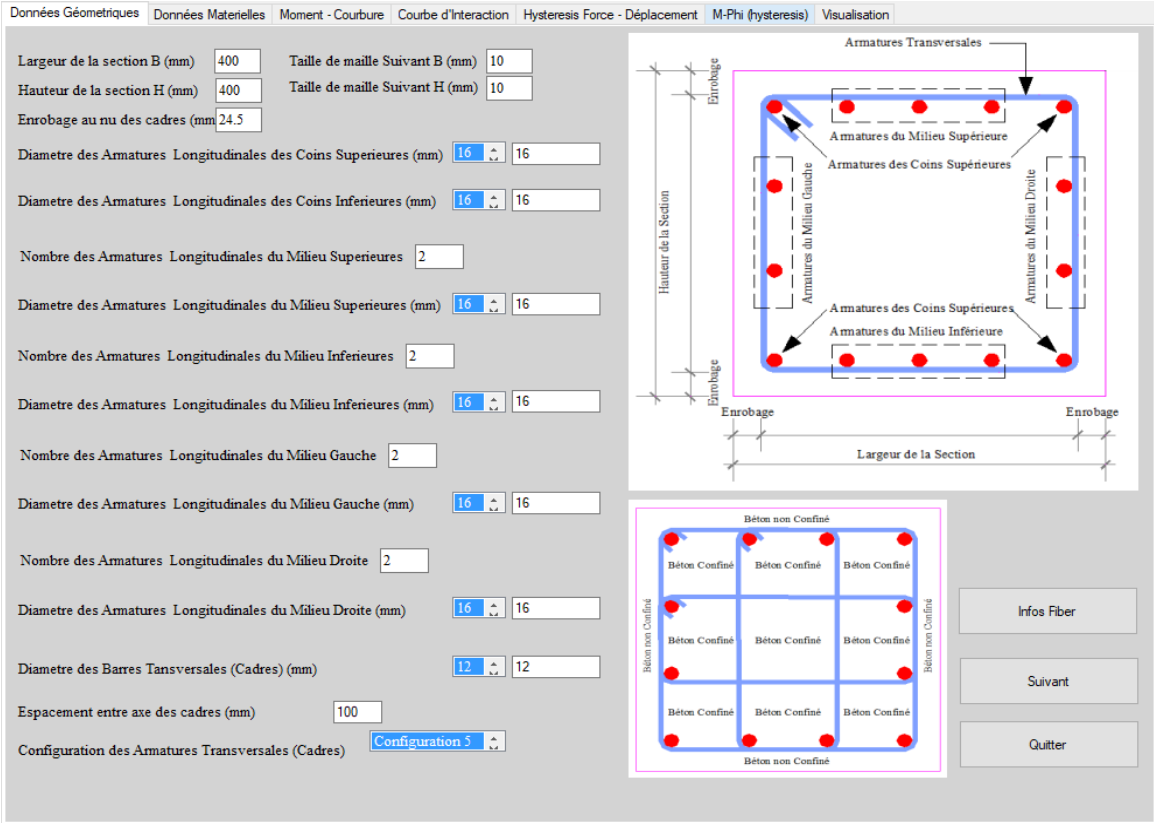

Fig. 2. Main window: definition of geometric characteristics of the cross section

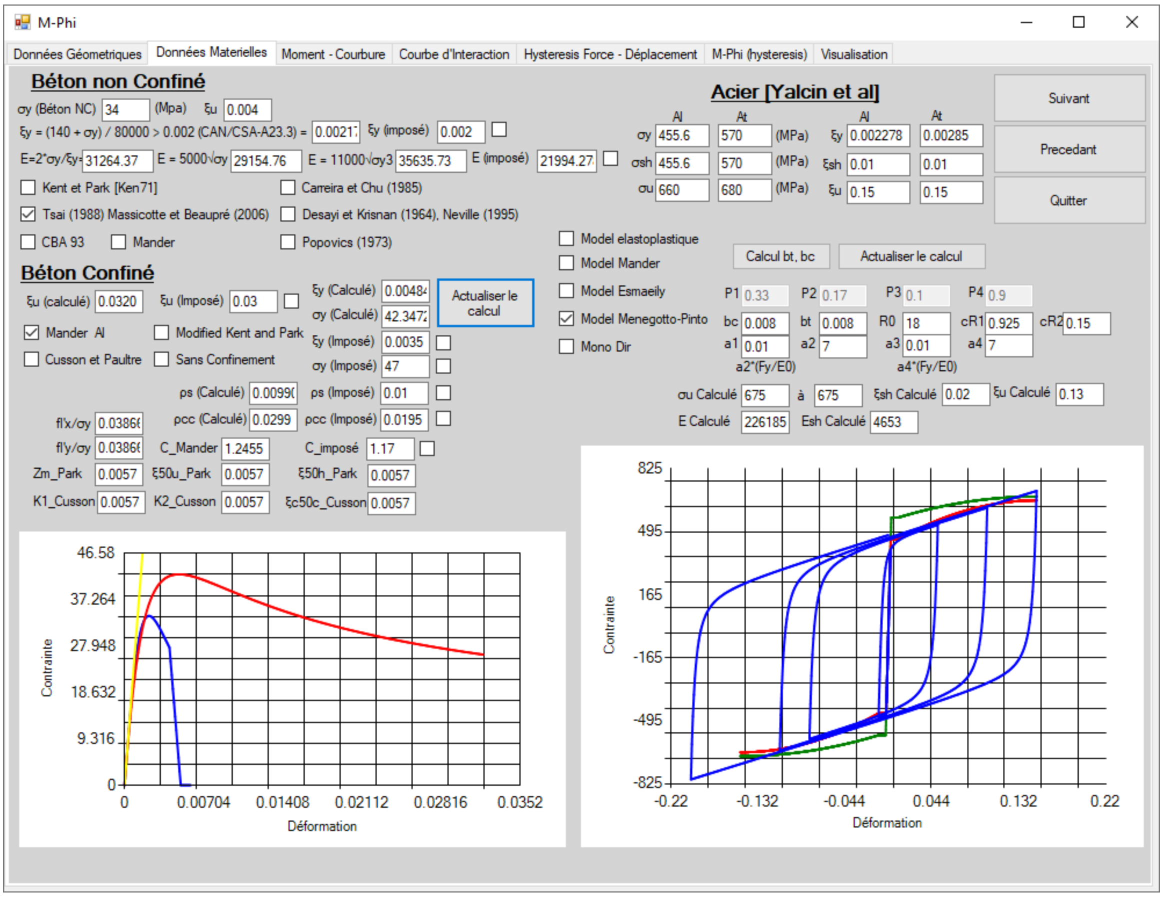

Fig. 3. Window for configuring the selected material models

model (Esmaeily and Peterman, 2007; Esmaeily and Shirmohammadi, 2014; Esmaeily-Ghasemabadi and Xiao, 2002; Shirmohammadi, 2015). Those models were selected for their ease of programming, extensive usage, and numerical stability.

Hinge plastic length calculation models

The user can select one of the four programmed methods (Fig. 4): Esmaeily & Xiao 2002 (Esmaeily and Shirmohammadi, 2014; Esmaeily-Ghasemabadi and Xiao, 2002; Shirmohammadi, 2015), Sheikh & Khoury 1993 (Mortezaei and Ronagh, 2013; Shirmohammadi, 2015; Zhao et al., 2011), Paulay & Priestley 1992 (Esmaeily and Shirmohammadi, 2014; Esmaeily-Ghasemabadi and Xiao, 2002; Mortezaei and Ronagh, 2013; Shirmohammadi, 2015; Zhao et al., 2011) and Priestly & Park 1987 (Esmaeily and Shirmohammadi, 2014; Esmaeily-Ghasemabadi and Xiao, 2002; Mortezaei and Ronagh, 2013; Priestley and Park 1987; Shirmohammadi, 2015; Zhao et al., 2011), and also manually define the plastic length.

Analysis process

Moment-curvature relation

The concrete in the analyzed section is divided into a number of fibers, and each steel reinforcement considered as a fiber (Fig. 6). Each fiber is associated with a series of data, including the type of material, area, and coordinates (Chadwell and Imbsen, 2004; Sato et al., 2002).

The strain at each fiber and the curvature are determined by the variation of the neutral axis and the strains from the most compressed to the most tensile fiber (Fig. 7) using the following relationships:

$$\varphi = {\varepsilon_{mc}}/{Y_{mc}} = {\varepsilon_{mt}}/{Y_{mt}}; \quad (1)$$

$$\varepsilon_i = \varphi \times (Y_i - Y_N), \quad (2)$$

where: φ — curvature, ε_{mc} — strains in the most compressed fiber, ε_{mt} — strains in the most tensile fiber, ε_i — strains in the fiber (i), Y_{mc} — coordinate of the most compressed fiber, Y_{mt} — coordinate of the most tensile fiber, Y_i — coordinate of the fiber (i), Y_N — coordinate of the neutral axis.

The stress in each fiber can be estimated using the calculated strain and the material model (stress-strain) adopted by the user (Fig. 3).

The position of the neutral axis, the curvature of the cross section, and the stress and strain state of each fiber will be determined, and the bending moment of the section can be evaluated using relationship (4), only if the equilibrium of relationship (3) between internal and external forces is satisfied.

$$P = FandF = \sum_{i=1}^{n} \sigma_{ci} * A_{ci} + \sum_{j=1}^{m} \sigma_{sj} * A_{sj}; \quad (3)$$

$$M = \sum_{i=1}^{n} \sigma_{ci} * A_{ci} * d_i + \sum_{j=1}^{m} \sigma_{sj} * A_{sj} * d_j, \quad (4)$$

where: P — external axial force, F — internal force in the section, M — moment in the section, σ_{ci} — stress in the fiber (*i*) of concrete, σ_{sj} — stress in the fiber (*j*) of a reinforcement bar, A_{ci} — area of

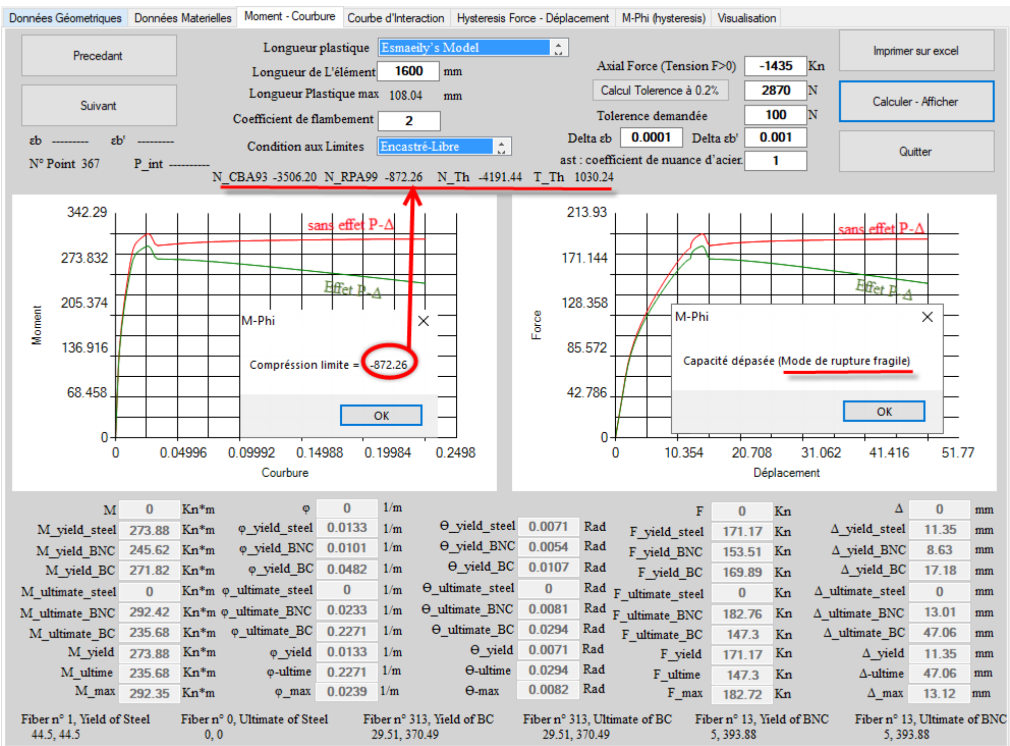

Fig. 4. Window for the analysis of a section under monotonic loading

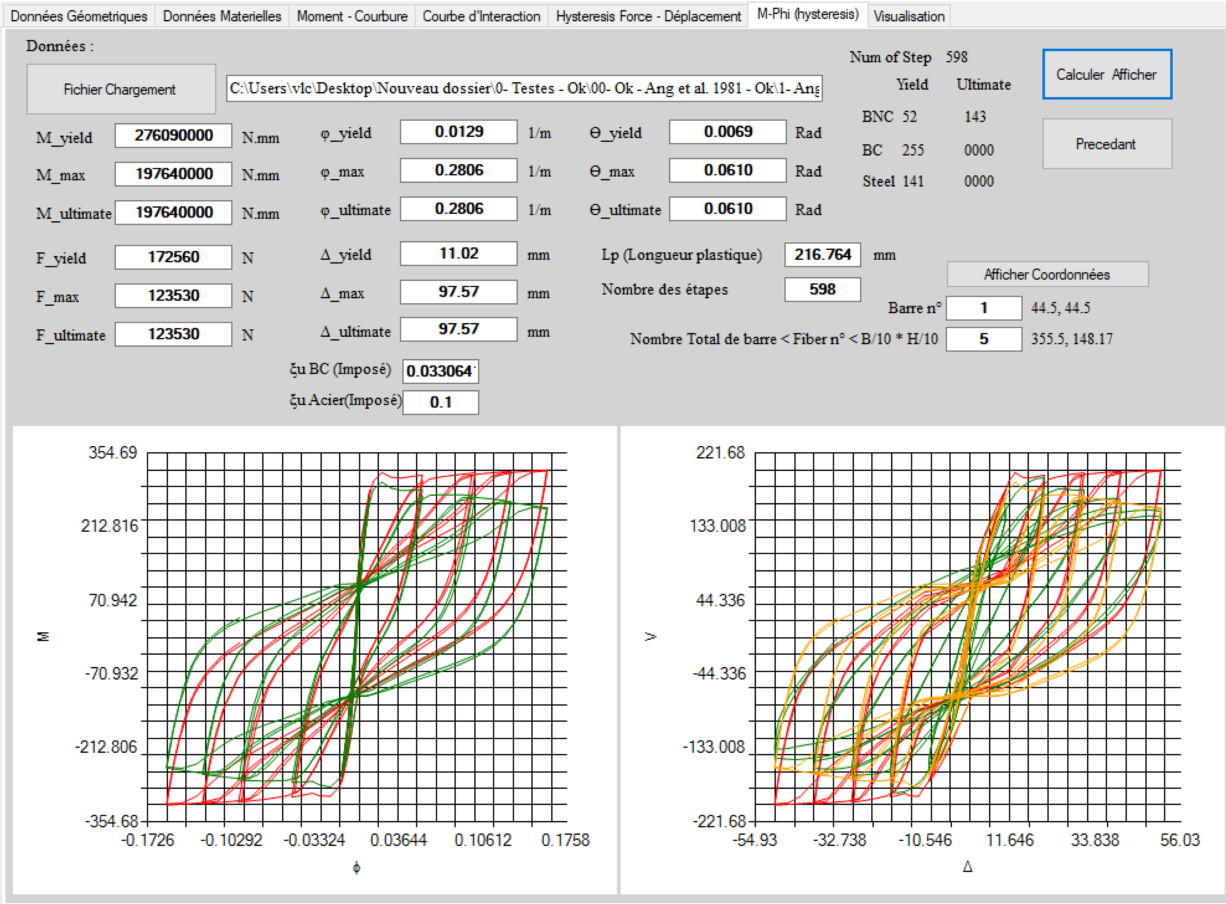

Fig. 5. Window for the analysis of a section under cyclic loading

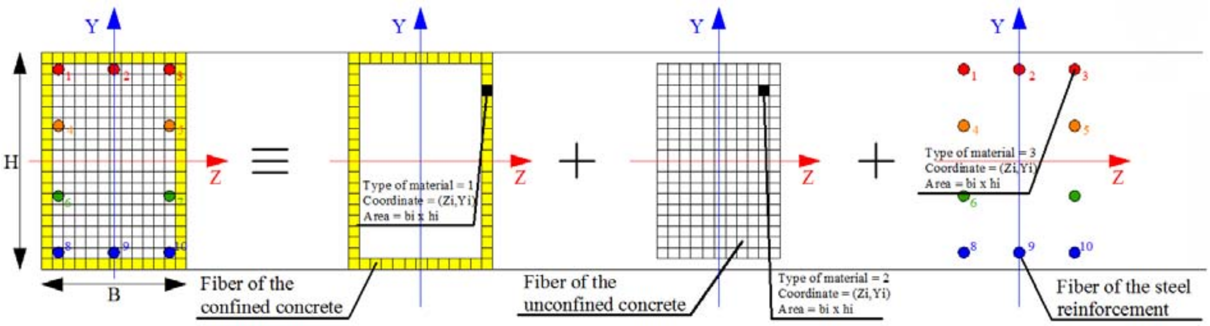

Fig. 6. Details of reinforced concrete section discretization

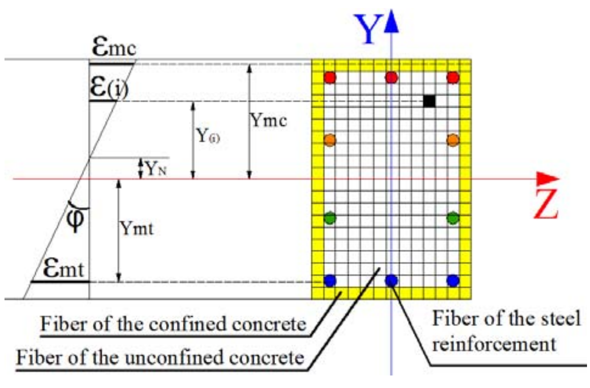

Fig. 7. Estimation of the strain in each fiber

the fiber (*i*) of concrete, A_{sj} — area of the fiber (*j*) of a reinforcement bar, d_i — coordinate of the fiber (*i*) of concrete, d_j — coordinate of the fiber (*j*) of a reinforcement bar.

Fig. 8 illustrates the numerical moment-curvature analysis algorithm for sections under monotonic loading.

Force-displacement relationship

The force-displacement analysis of the element is based on the moment-curvature analysis. Before conducting the monotonic or cyclic analysis, the user must determine the loading history, member length, and plastic hinge method (Figs. 4 and 5). The force-displacement curve will be determined using the following relationships:

$$\Delta = \begin{cases} \varphi_{calc} \le \varphi_y \varphi_{calc} \times L^2/3; \\ \varphi_y \le \varphi_{calc} \le \varphi_u \left[\varphi_y \times L^2/3\right] + \\ + \left[L_p \times \left(\varphi_{calc} - \varphi_y\right) \times \left(L - 0.5L_p\right)\right]; \end{cases} \quad (6)$$

$$F = M / L. \quad (7)$$

Fig. 9 illustrates the numerical force-displacement analysis algorithm for sections under monotonic and cyclic loading.

Convergence analysis of the program

The convergence analysis serves as a comprehensive validation of the program reliability and accuracy in predicting the behavior of reinforced concrete elements under both monotonic and cyclic loading. To evaluate the performance and efficiency of the computer program developed, the data from several experimental tests were input into the program (Table 1).

The Mander model (Mander, 1983; Mander et al., 1988) is used to simulate the uniaxial stress-strain relationship of confined and unconfined concrete fibers with an elastoplastic hysteresis law, while the Giuffrè–Menegotto–Pinto model (Bosco et al., 2016; Carreño et al., 2020; Menegotto and Pinto, 1973; opensees.berkeley.edu, 2023) is used for modeling the stress-strain relationship of the longitudinal reinforcing bars. The numerical results obtained from the simulation are then compared with the corresponding experimental results.

Presentation and discussion of the results

In this section, several results are presented and discussed, including hysteresis loops, force-displacement envelope curves, maximum resistance, initial stiffness, stiffness degradation, and cumulative energy dissipation.

Hysteresis loops

The hysteresis behavior, the shear force history at each analysis step, and the shear force at the peak of the first cycle of each imposed displacement resulting from the simulation are presented in Fig. 10 and compared with the results of the experimental tests.

The ratio between the simulated shear force and the experimental shear force, calculated at the peak of the first cycle of each imposed

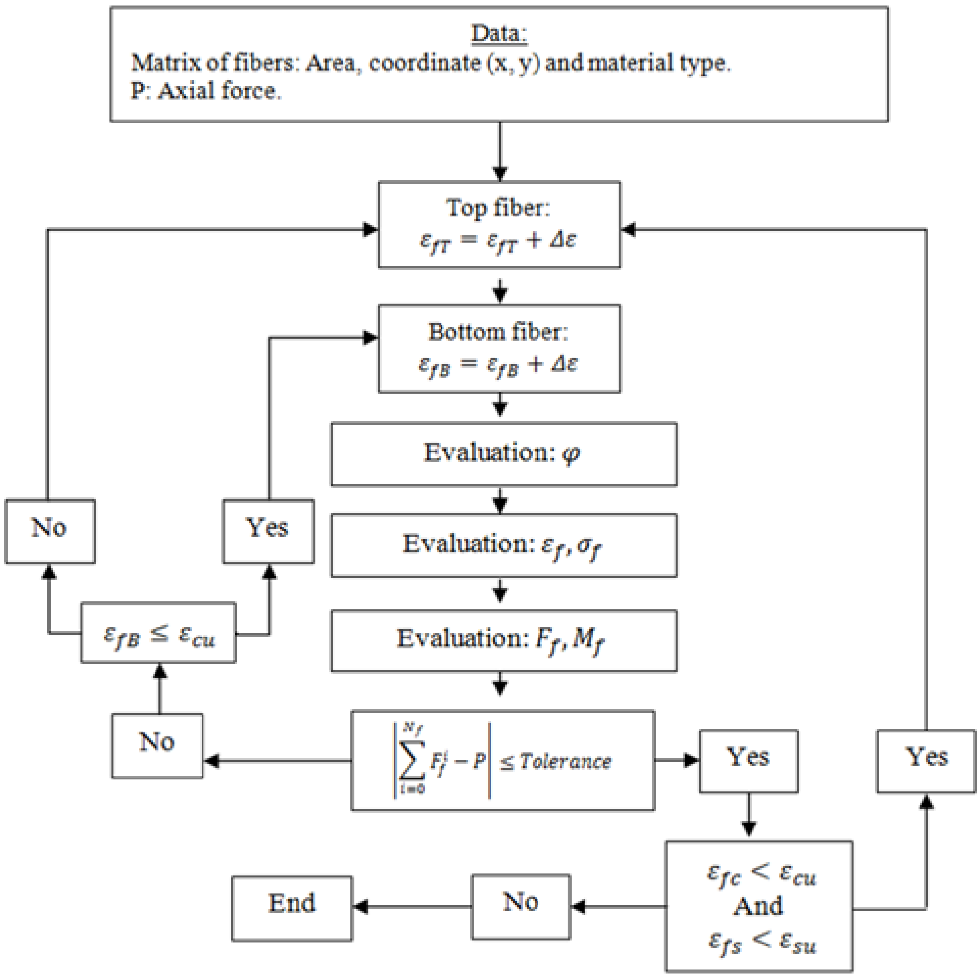

Fig. 8. Numerical moment-curvature analysis algorithm for sections under monotonic loading

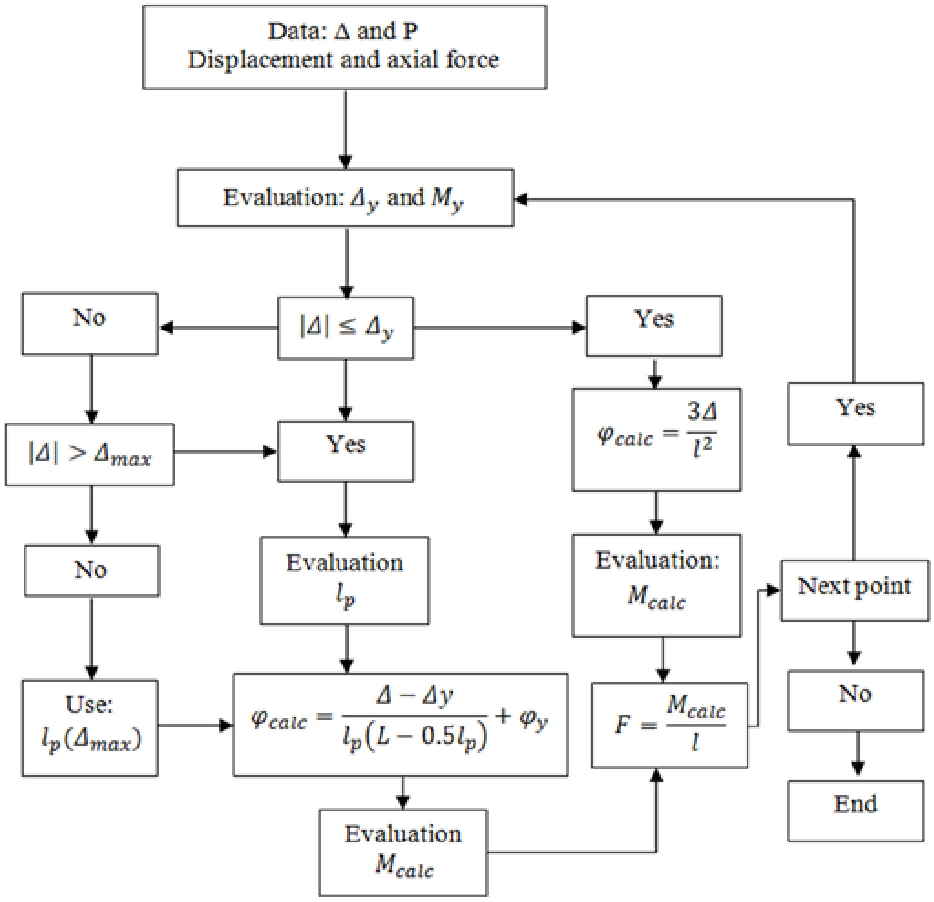

Fig. 9. Numerical force-displacement and moment-curvature analysis algorithm for sections under cyclic loading: Δ — displacement, Δ_y — yield displacement, Δ_{max} — maximum displacement, φ_y — yield curvature, φ_{calc} — calculated curvature, l — element length, l_p — plastic hinge length, $l_p(\Delta_{max})$ — plastic hinge length at maximum displacement, M_y — yield moment, M_{calc} — calculated moment, and F — internal force

displacement, shows (Fig. 10c) a good correlation between the numerical model and the experimental results for most tests (0.02 to 13.75 %) and a variation of the order of 19.14 to 33.07 % for the two tests: test h (Alfarah, 2017; Maranhão et al., 2021; nisee.berkeley.edu, 2003; Tanaka, 1990) and test i (nisee.berkeley.edu, 2003; Park and Paulay, 1990), probably associated with a linear elastic numerical response.

In general, a good representation of the global response of the elements is obtained. In the majority of cases, it was also observed that the cyclic unloading response phase of the columns obtained with the numerical models does not capture the pinching effect observed experimentally.

Envelope capacity curves

A good agreement was found between the experimental test capacity curves and those of the computer program. The envelope curves obtained based on the cyclic responses are shown in Fig. 11.

Initial stiffness

The ratio between the experimentally determined initial stiffness and the values obtained numerically was calculated and illustrated in Fig. 12 to evaluate the program accuracy in terms of initial stiffness.

The initial stiffness K_i is the ratio between the shear force and the displacement corresponding to the yield point. Based on the results obtained, it can be concluded that:

- For the following tests: test a (Atalay and Penzien, 1975; nisee.berkeley.edu, 2003), test b (Ang, 1981; nisee.berkeley.edu, 2003), test c (Ang, 1981; nisee.berkeley.edu, 2003), test d (nisee.berkeley.edu, 2003; Ohno and Nishioka, 1984), test e (nisee.berkeley.edu, 2003; Ohno and Nishioka, 1984), test f (nisee.berkeley.edu, 2003; Tanaka, 1990), test g (nisee.berkeley.edu, 2003; Tanaka, 1990), and test h (Alfarah, 2017; Maranhão et al., 2021; nisee.berkeley.edu, 2003; Tanaka, 1990), the computer program provides a good estimate of the initial stiffness with a variation of 0–19 %.

- There is a significant variation in the initial stiffness between the experimental test (nisee.berkeley.edu, 2003; Park and Paulay, 1990) and the program, with an overestimation of the initial stiffness

Table 1. **Geometric and material characteristics of the specimens used in the simulation**

Symbol	Test	Specimen	*B*×*H* (mm²)	*L* (m)	*N* (KN)	σ_c (MPa)	σ_s (MPa)	ρ_s (%)	σ_t (MPa)	ρ_t (%)
a	Atalay and Penzien 75 (Atalay and Penzien 1975; nisee.berkeley.edu, 2003)	3S1	305 x 305	1676	267	29.2	367	1.63	363	1.5
b	Ang 81 (Ang, 1981; nisee. berkeley.edu, 2003)	S3	400x400	1600	1435	23.6				
c	Ang 81 (Ang, 1981; nisee. berkeley.edu, 2003)	S4	400x400	1600	840	25.0	427	1.51	280	2.2
d	Ohno and Nishioka 84 (nisee.berkeley.edu, 2003; Ohno and Nishioka, 1984)	L1	400x400	1600	127	24.8	362	1.42	325	0.3
e	Ohno and Nishioka 84 (nisee.berkeley.edu, 2003; Ohno and Nishioka, 1984)	L2	400x400	1600	127	24.8	362	1.42	325	0.3
f	Tanaka & Park 90 (nisee. berkeley.edu, 2003; Tanaka, 1990)	No. 1	400x400	1600	819	25.6	474	1.57	333	2.5
g	Tanaka & Park 90 (nisee. berkeley.edu, 2003; Tanaka, 1990)	No. 4	400x400	1600	819	25.6	474	1.57	333	2.5
h	Tanaka & Park 90 (Alfarah, 2017; Maranhão et al., 2021; nisee. berkeley.edu, 2003; Tanaka, 1990)	No. 6	550x550	1650	968	32.0	511	1.25	325	1.7
i	Park and Paulay 90 (nisee.berkeley.edu, 2003; Park and Paulay, 1990)	No. 9	400x600	1784	646	26.9	432	1.88	305	2.2

Where: *B* — element width, *H* — element depth, *L* — element length, *N* — axial load, σ_c — concrete strength, σ_s — yield strength of longitudinal reinforcement, ρ_s — longitudinal reinforcement ratio, σ_t — yield strength of transverse reinforcement, ρ_t — transverse reinforcement ratio.

by 33 %. This overestimation could be explained by an underestimation of the yield displacement obtained from the program.

Maximum strength

The maximum strength ratio between program simulations and experimental tests is calculated at the maximum imposed displacement of each hysteresis curve.

The maximum strength ratio clearly demonstrates the effectiveness of the program in predicting the maximum strength of reinforced concrete elements (Fig. 13) with satisfactory accuracy (0.07–11.80 %).

Stiffness degradation

The evolution of stiffness degradation as a function of relative imposed displacement is shown in Fig. 14. The relative stiffness is the ratio of the stiffness at the peak of the first cycle of each imposed displacement and the initial stiffness.

Based on the results obtained, it can be noticed that the program provides a good estimate of the stiffness degradation for the various specimens. It can be said that the program accuracy is excellent in representing the stiffness degradation of reinforced concrete elements.

Cumulative energy dissipation

The evolution of the dissipated energy (Fig. 15) and the cumulative energy dissipation (Fig. 16) for each specimen was determined and compared with the results obtained by the computer program. Based on the results obtained, it can be concluded that:

• In general, the results for all tested elements show a very good correlation between the experimental dissipated energy and the program's dissipated energy. Nevertheless, an underestimation of the cumulative energy dissipation for relative imposed displacement of the order of 0 to 1 %, associated with a quasi-linear numerical response, and a slight overestimation for relative imposed displacement greater than 1 % was observed. This slight overestimation of the cumulative energy dissipation could be justified by the inadequacy of the numerical models in representing the pinching effect in experimentally observed hysteresis loops.

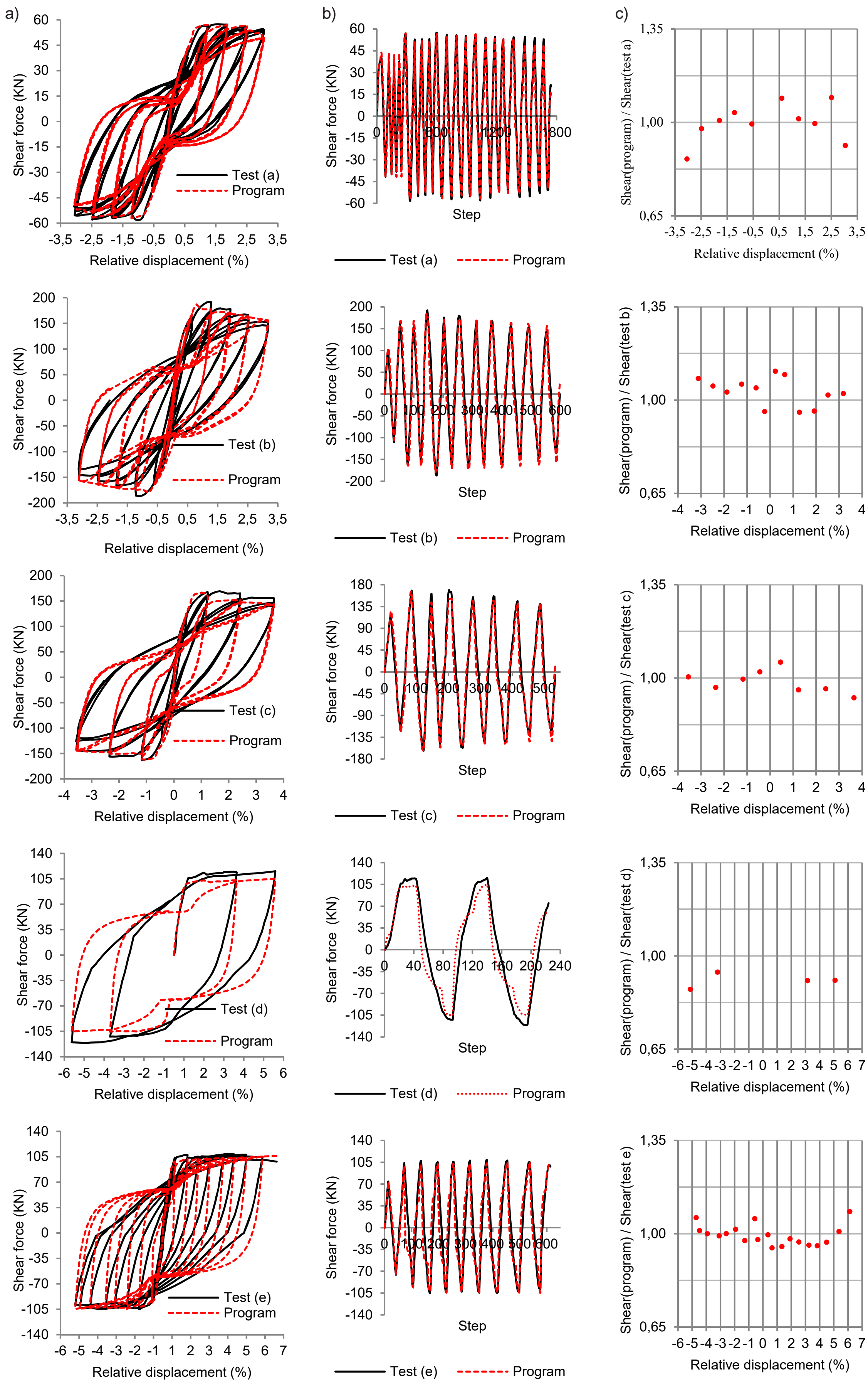

Fig. 10. (a) hysteresis shear force – relative displacement, (b) shear force history at each analysis step, (c) ratio of the simulated shear force to the test shear force (beginning)

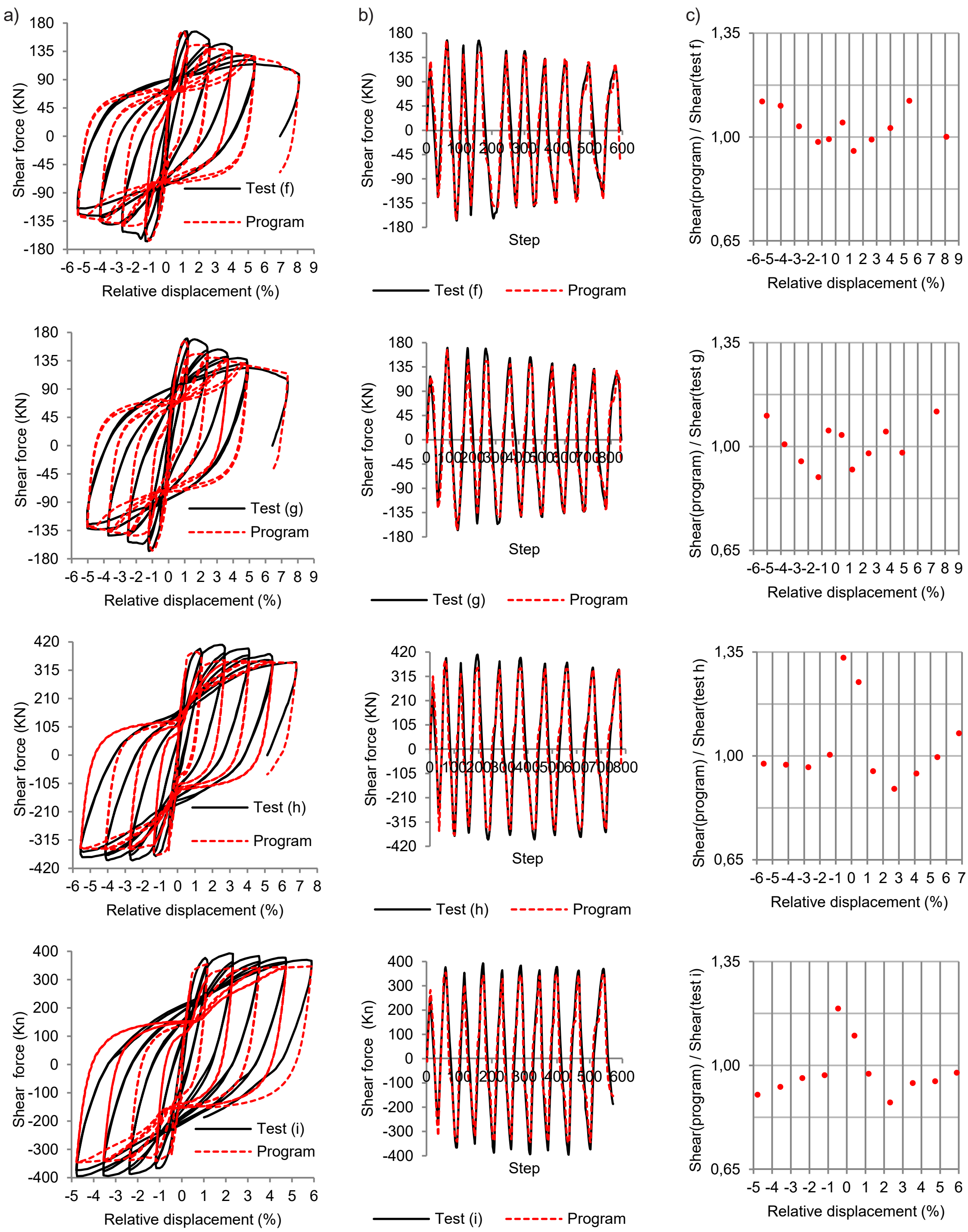

Fig. 10. (a) hysteresis shear force – relative displacement, (b) shear force history at each analysis step, (c) ratio of the simulated shear force to the test shear force (ending)

The convergence analysis in this paper assesses the predictive accuracy of the developed interactive computer program for the nonlinear behavior of reinforced concrete elements under monotonic and cyclic lateral loading. The program utilizes a fiber element approach with various material models and hysteresis laws. Hysteresis loops are examined, revealing a strong correlation between numerically simulated and experimental shear forces. Force-displacement envelope curves demonstrate the program's ability to accurately predict the overall response of reinforced concrete elements, affirming its efficacy in estimating maximum resistance. The initial stiffness estimation generally aligns with the experimental values, but a notable discrepancy in one test suggests potential areas for improvement. The maximum strength ratio analysis confirms the program's effectiveness in predicting maximum strength. The assessment of stiffness degradation indicates that the program provides a good

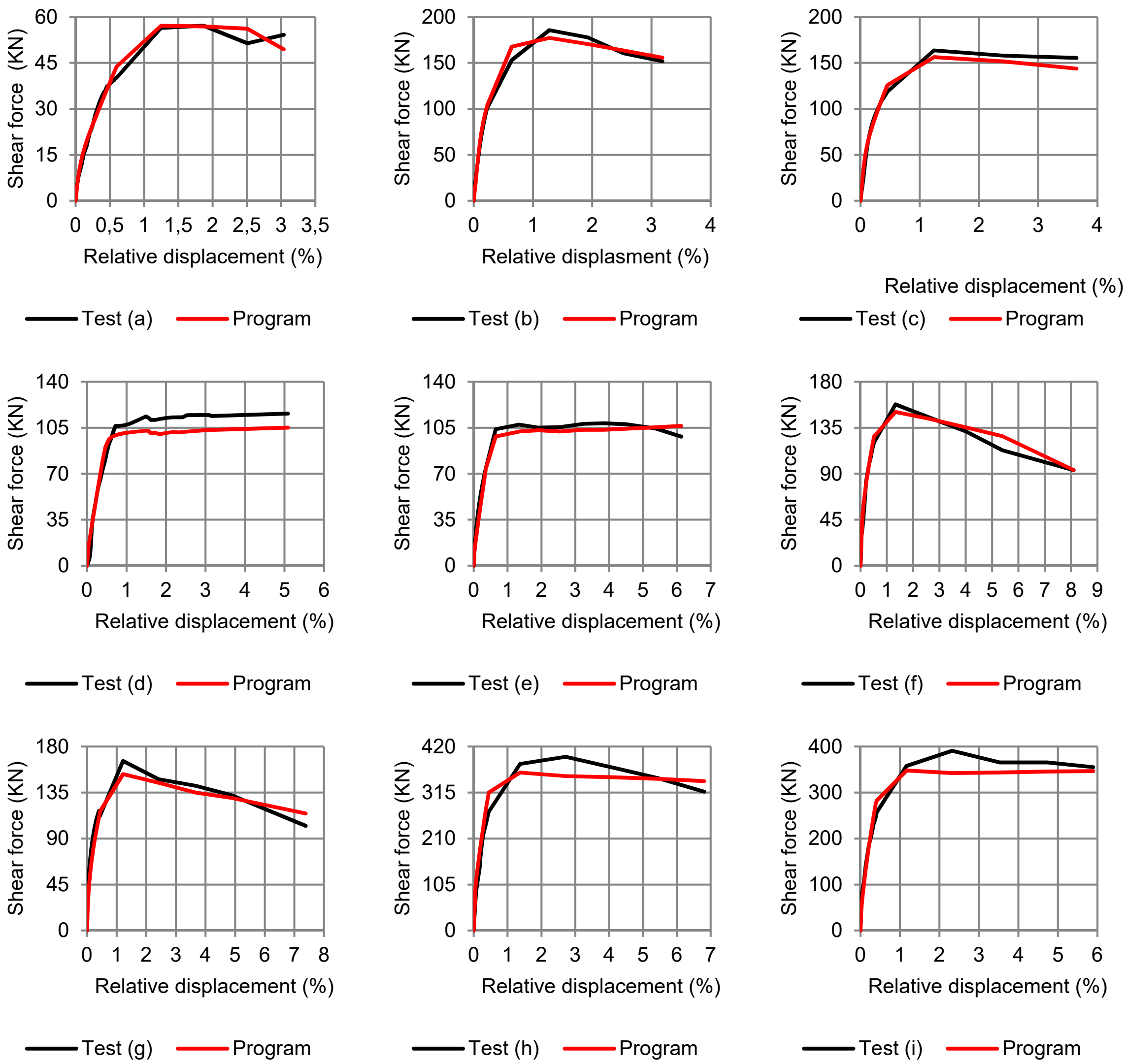

Fig. 11. Envelope capacity curves

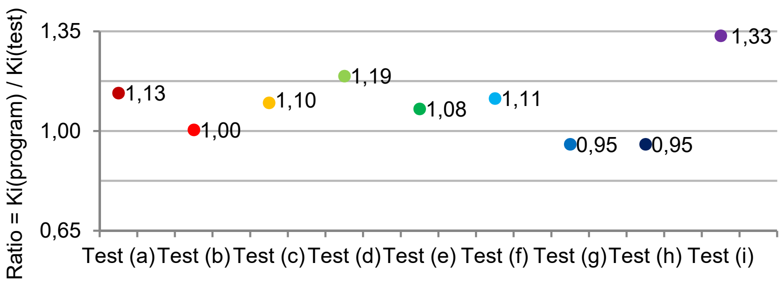

Fig. 12. Initial stiffness ratio

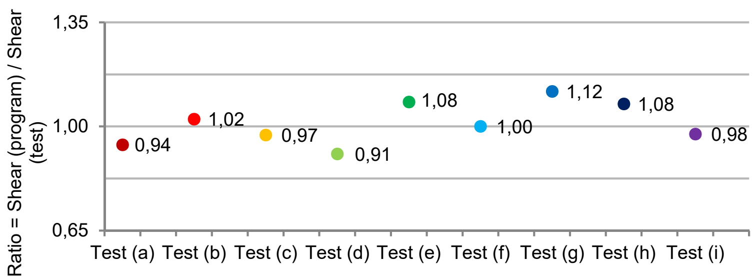

Fig. 13. Maximum strength ratio

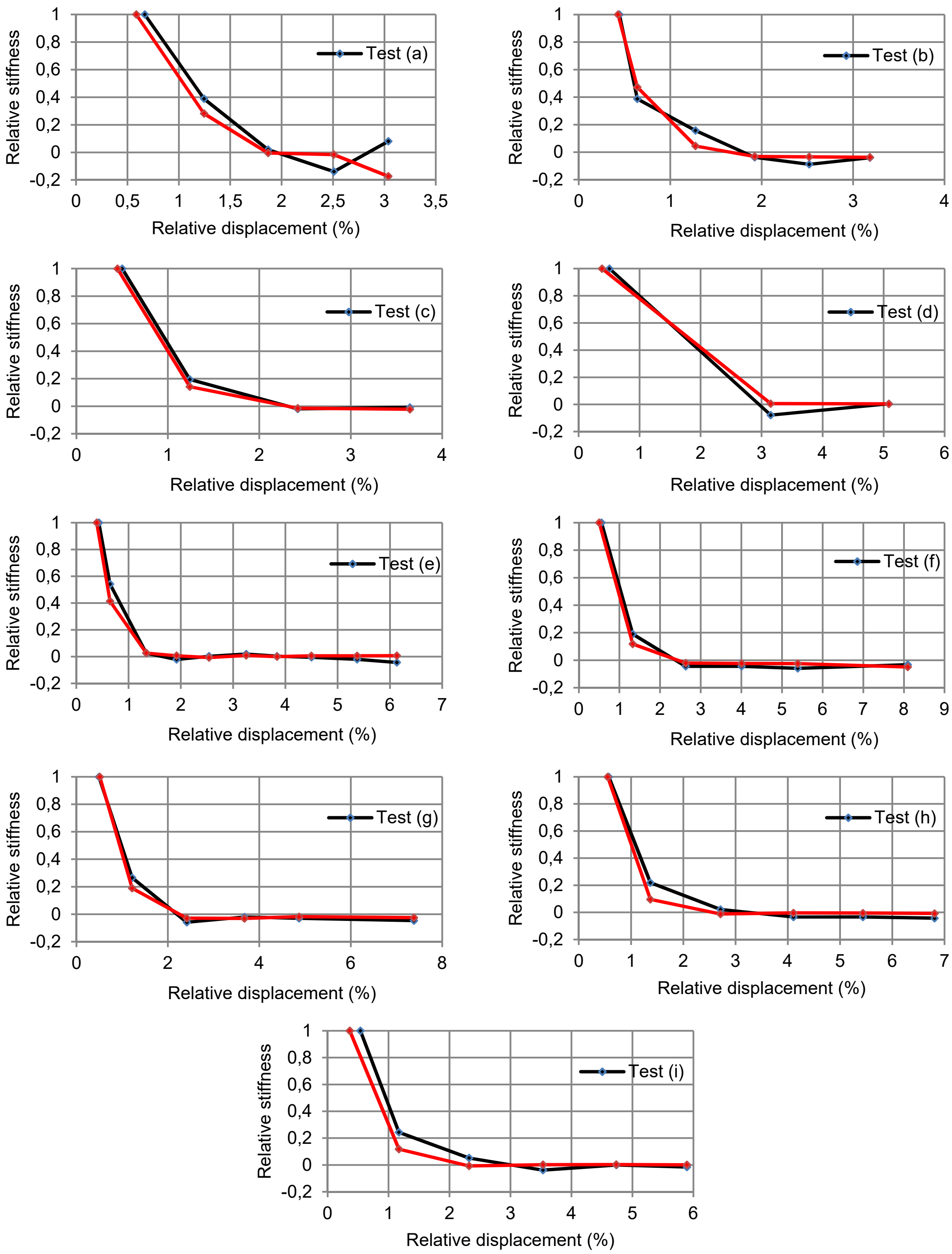

Fig. 14. Stiffness degradation as a function of relative displacement demand

estimation of degradation across various specimens. Cumulative energy dissipation analysis reveals a strong correlation between experimental and program-predicted dissipated energy, with minor differences attributed to numerical model limitations. Overall, the convergence analysis validates the program's reliability and accuracy in predicting reinforced concrete element behavior under both monotonic and cyclic loading, substantiating its suitability for engineering applications.

Conclusion

In conclusion, this study has successfully developed and validated a computer interactive program designed to predict the nonlinear behavior of reinforced concrete columns under both monotonic and cyclic loading conditions, utilizing established

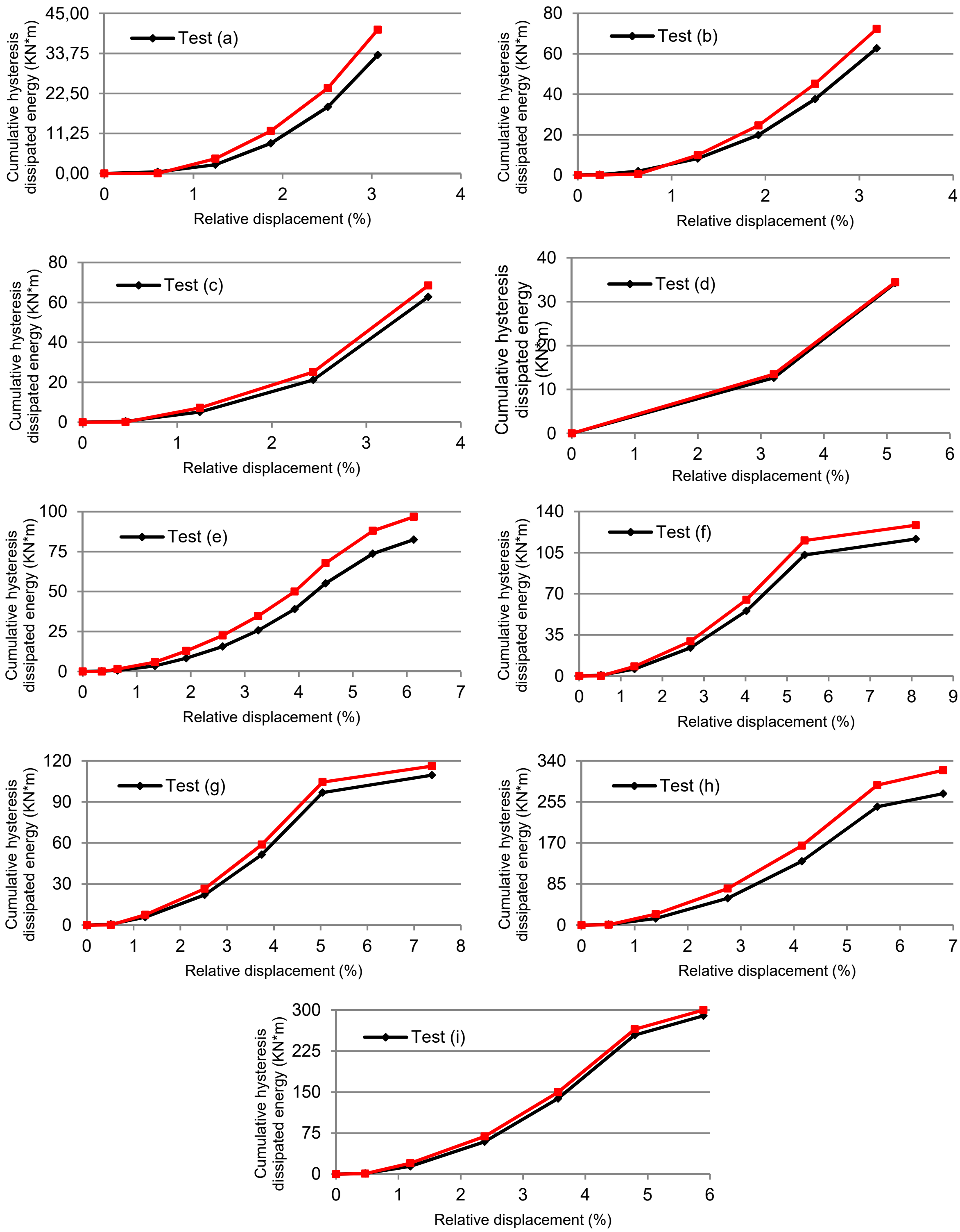

Fig. 15. Cumulative energy dissipation in relation to relative displacement demand

models for concrete stress-strain relationships and reinforcing steel behavior.

The results of the convergence analysis show a strong correlation with the experimental data, further enhancing the reliability and accuracy of the program. This showcases the program's efficiency in simulating the behavior of reinforced concrete elements, particularly in terms of maximum resistance and initial stiffness. Despite limitations in representing the pinching effect during unloading-reloading phases and some differences in energy dissipation, the program proves to be very efficient and sufficiently accurate.

Furthermore, the program's capability to perform realistic nonlinear analysis of reinforced concrete

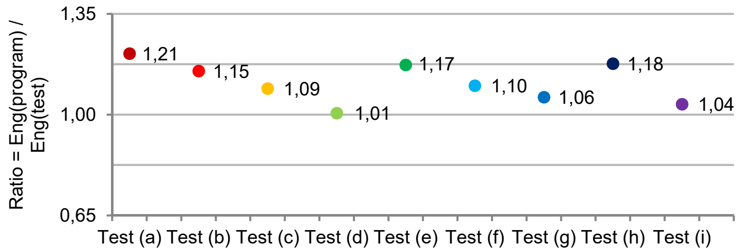

Fig. 16. Ratio between the simulated cumulative energy dissipation and the actual cumulative energy dissipation in the tests

element behavior can prove to be very useful for various parametric studies. It is a valuable tool for examining the effectiveness of certain material models against experimental tests and serves as a good learning aid in graduate university classes and continuing education. The program's user-friendly interface and graphical representations make it a valuable tool for concrete research within earthquake engineering and a practical asset for design offices.

In summary, the developed program, with its robust numerical tools and innovative applications, stands as a promising tool for researchers, engineers, and educators involved in the analysis and design of concrete structures, particularly in the context of seismic considerations.

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ПРОГНОЗИРОВАНИЕ ЭКСПЛУАТАЦИОННЫХ ХАРАКТЕРИСТИК ЖЕЛЕЗОБЕТОННЫХ ЭЛЕМЕНТОВ ПРИ МОНОТОННОМ И ЦИКЛИЧЕСКОМ БОКОВОМ НАГРУЖЕНИИ

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Аннотация
Введение: Основной целью данной работы является изучение нелинейного поведения железобетонных элементов при монотонном и циклическом нагружении. За последние 30 лет было проведено несколько экспериментальных исследований с целью получения более полного представления о нелинейном поведении железобетонных элементов и определения различных параметров, влияющих на это поведение. **Цель исследования:** Данное исследование изучает это поведение и направлено на разработку интерактивной компьютерной программы, предназначенной для использования в среде Windows. **Методы:** В аналитическом подходе с применением волокнистого элемента используются несколько моделей материалов (железобетон с поперечным армированием / железобетон без поперечного армирования и арматурная сталь), а также законы гистерезиса Для каждого образца в программу введены геометрические характеристики, модели материалов, варианты расположения пластических шарниров, осевые нагрузки и история соответствующих горизонтальных перемещений. Численные прогнозы проверены и подтверждены результатами экспериментальных испытаний, проведенных различными авторами. **Результаты:** Результаты моделирования оказались очень близки к экспериментальным, особенно для петель гистерезиса, огибающих кривых силы-перемещения, начальной жесткости, снижения жесткости, максимальной прочности и кумулятивной диссипации энергии. Программа способна прогнозировать нелинейное поведение железобетонных элементов. Разработанная программа представляет собой надежный инструмент для прогнозирования нелинейного поведения железобетонных элементов при циклическом нагружении. Точность подтверждена анализом сходимости с экспериментальными данными.

Ключевые слова: компьютерная программа, волокнистый элемент, гистерезис, модели материалов, момент-кривизна.