12th International Conference on Advances in Steel-Concrete Composite Structures (ASCCS 2018)
Universitat Politècnica de València, València, Spain, June 27-29, 2018
Doi: http://dx.doi.org/10.4995/ASCCS2018.2018.7162

Simplified modelling of circular CFST members with a Concentrated Plasticity approach

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Abstract

The research reported herein aims at proposing an accurate and efficient simplified numerical modelling approach for circular Concrete-Filled Steel Tubular (CFST) columns under flexural loading. Experimental tests were carried out to characterize the monotonic and cyclic behaviour of CFST members under bending. To assess the seismic performance of a composite structure with CFST members, both Distributed Plasticity (DP) and Concentrated Plasticity (CP) models were considered. The DP model was developed on the basis of a fibre discretization of the composite cross-section and displacement-based beam-column finite element. It was concluded that one could not accurately capture the development of local buckling of the steel tube and the development of multi-axial stress state effects (e.g. concrete confinement). Regarding the CP model, the modified Ibarra-Medina-Krawinkler deterioration model (with peak-oriented hysteretic response) was selected to simulate the nonlinear behaviour of the plastic hinge region of a CFST member. In order to accurately simulate the cyclic behaviour of the CFST section within the response of the spring, the deterioration model was calibrated, within a parameter-optimization framework, on the basis of 3D comprehensive numerical models in ABAQUS. The CP model was found to capture well the deterioration in both strength and stiffness of the hysteretic loops of the CFST members, which legfely results from the development of local buckling effects of the steel tube. Furthermore, the elastic stiffness, the ultimate strength and the pinching effects of the hysteretic loops were also well simulated. The proposed CP model, coupled with the advanced calibration framework, results in a high level of accuracy in terms of simulating the cyclic flexural response of composite structures made with CFST members.

Keywords: *Concrete-filled steel tube; concentrated plasticity model; seismic performance; OpenSees.*

1. Introduction

The enhanced seismic performance of Concrete-Filled Steel Tubular (CFST) members is drawing the attention of structural engineers. To evaluate the seismic performance of a composite structure with such members, reliable numerical modelling techniques are crucial. Two approaches are oftern adopted for the simplified modelling of CFST members, namely a Distributed Plasticity (DP) approach and a Concentrated Plasticity (CP) approach. Regarding the DP model, it consists on a fibre-based representation of the section shape, coupled with uniaxial material properties of the CFST parts. An important drawback is associated with such modelling approach, namely the fact that it neglects any interaction effects between the different parts of the section (e.g. concrete confinement and steel tube local buckling). Thus, the usage of a DP model may play an important role on the reliability of the numerical simulation, particularly when one is interested in evaluating structural response at extreme loading scenarios. In particular, the two aforementioned mechanisms have a significant influence on the cyclic flexural behaviour of CFST members [1-3]. Compared to the DP model, the CP model is able to simulate composite effects and the effect of local buckling [4], despite not accounting for the interaction between axial load and bending moment. Furthermore, to develop an accurate CP model for CFST members, a reliable definition of the moment-rotation behaviour of the member is required.

This paper focuses on the proposal of a simplified modelling approach for CFST members with a concentrated plasticity approach. Based on experimental data and advanced 3D FE models, which are used to provide the target data, the CP models are calibrated to accurately simulate the response of these composite members. Based on the comparison between analytical results and test data, the disadvantages of the DP model are discussed. The CP model for CFST members is developed in terms of a material hysteretic rule which is calibrated based on an advanced calibration framework. To verify the feasibility of the developed CP model, the cyclic responses from the 3D FE model analysis and the calibrated CP model are compared.

2. Experimental tests and 3D FE model

To characterize the seismic behaviour of circular CFST members, several experimental tests were conducted by the authors [1]. Based on the test results, a detailed 3D Finite Element (FE) model, which aimed to provide the target data for the calibration of numerical models, was developed in ABAQUS [5]. In the following subsections, both the test observations and the detailed FE model are described.

2.1. Test observation

A number of experimental tests were carried out to investigate the flexural behaviour of circular CFST members [1]. The specimen details are listed in *Table 1*, where *D* is the external diameter, *t* is the steel tube thickness and *P* is the constant axial load level.

Table 1. The specimen details

No.	*D* [mm]	*t* [mm]	f_c [MPa]	f_y [MPa]	*P* [kN]
1	219	2.8	20	309	0
2	219	2.8	20	309	222
3	219	2.8	20	309	0
4	219	2.8	20	309	222
5	219	4.7	20	393	0
6	219	4.7	20	393	290
7	219	4.7	20	393	0
8	219	4.7	20	393	290
9	219	4.7	39	393	0
10	219	4.7	39	393	359
11	219	4.7	39	393	0
12	219	4.7	39	393	359
13	219	4.7	53	393	0
14	219	4.7	53	393	393
15	219	4.7	53	393	0
16	219	4.7	53	393	393

Generally, in the monotonic and cyclic tests, all specimens developed local buckling in the plastic hinge region. Fig. 1 shows the lateral force versus drift ratio plots of two CFST specimens under monotonic (specimen No.4) and cyclic lateral loading (specimen No.6), respectively. The two specimens have the same external diameter *D* = 219*mm* and steel tube thickness *t* = 5*mm*. The drift ratio is defined as the ratio between the lateral displacement and the specimen's length (1.35m). For monotonic lateral loading, little to no strength degradation was observed in the tests, even for high levels of lateral deformation, in which local buckling of the steel tube was clearly visible. This indicated that the CFST specimen exhibited ductile behaviour under monotonic loading, as the concrete core delayed the occurrence of local buckling and minimized its influence on the response. Regarding the cyclic behaviour, significant strength deterioration was observed, which was mainly due to the continuous development of local buckling at the plastic hinge region, which, for thin-walled specimens, even led to fracture of the steel tube. Therefore, the cyclic response of CFST members is generally more sensitive to this phenomena, in comparison to monotonic loading. Moreover, some pinching effects were also observed in the response, suggesting that the opening and closing of the concrete cracks within the concrete core also influenced the overall response of the member.

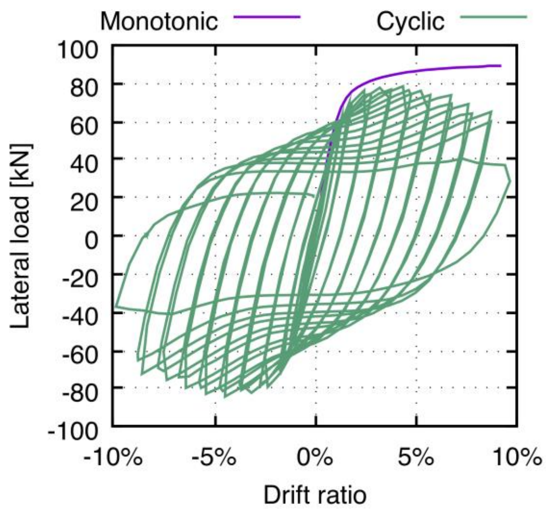


Fig. 1. Lateral load versus drift ratio curves - Comparison between specimens under monotonic and cyclic loading

2.2. 3D FE model

Based on the obtained test results, a detailed 3D FE model, which can simulate the effect of concrete confinement and local buckling of the steel tube, was developed in ABAQUS. As shown in Fig. 2, the model consists of a combination of solid (for the concrete core) and shell finite elements (for the steel tube). The detailed modelling techniques, namely the geometry, material constitutive law and interaction definition, are thoroughly described in [5].

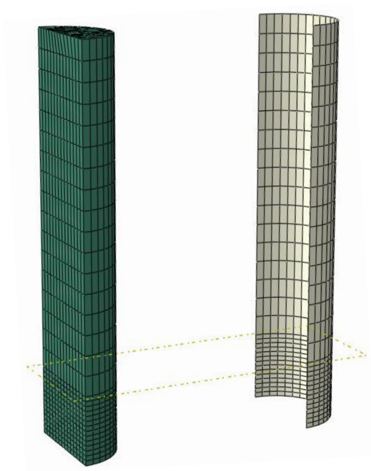


Fig. 2. Geometry of the 3D FE model

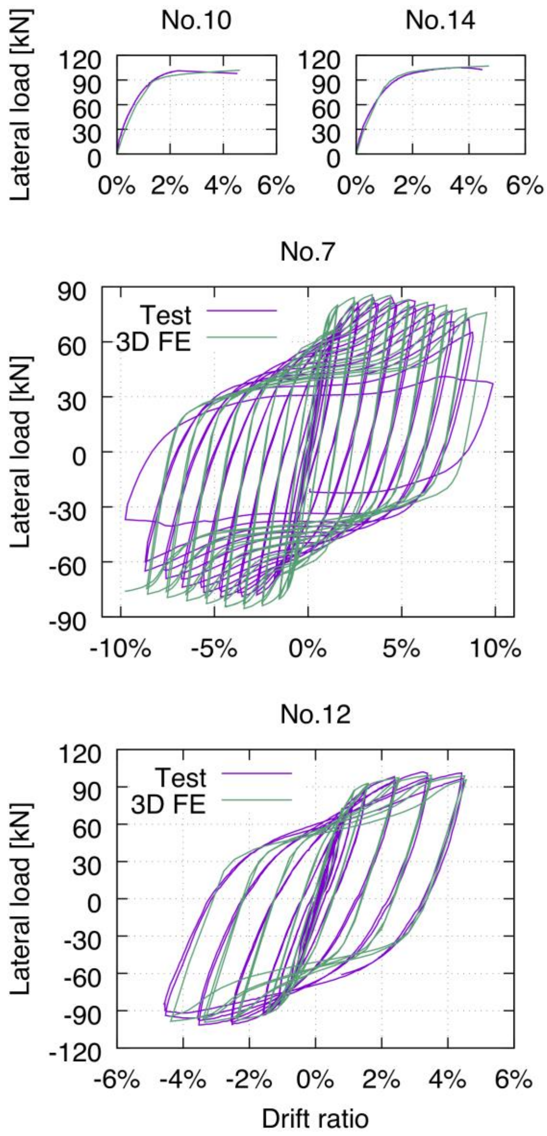


Fig. 3. Lateral load versus drift ratio curves comparisons between test results and 3D FE model prediction

Fig. 3 shows the lateral load versus drift ratio responses between the test results and the numerical simulation. For specimens under monotonic loading, the initial stiffness, yield strength and ultimate capacity are well captured. For members under cyclic bending, strength deterioration and pinching effects are also well represented by the proposed 3D FE model. Therefore, it could be confirmed that the 3D FE model could predict the flexural response of CFST members with accuracy. Thus, the analytical results from the model could be used in the calibration of simplified models.

3. Simplified numerical models

Despite the accuracy of the detailed model described before, such modelling strategy is not suitable for the analysis at a structure's level, which is mainly due to its high computational cost. Thus, two commonly adopted simplified models, namely the Distributed Plasticity (DP) model and the Concentrated Plasticity (CP) model (see Fig. 4), were considered as possible solutions for a structural-level analysis. In this section, the DP model and the CP model, which are developed in OpenSees [6], are described. Their feasibility for simulating the cyclic behaviour of CFST member is examined.

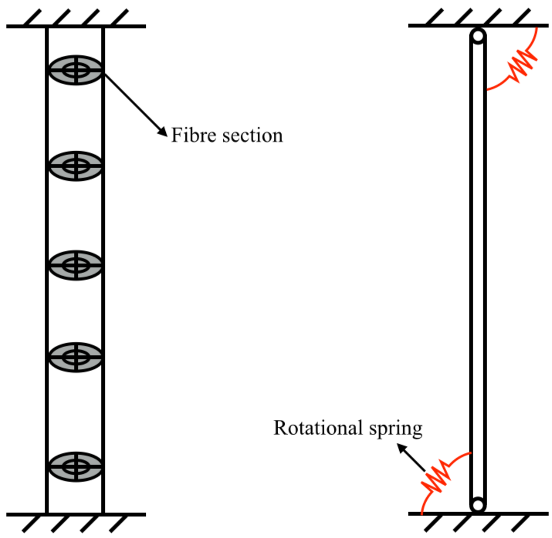


Fig. 4. The sketch map of DP and CP models

3.1. Distributed Plasticity model

As shown in Fig. 4 (left), the DP model consists of a beam-column element with a fibre-based discretization of the section along the member length. In this research, a displacement based beam-column element was adopted. Regarding the concrete and steel materials, the OpenSees built-in model *steel02* and *concrete02* models were used. The model details are described in [3]. As verified in [3], the DP model could accurate simulate the response of the tested CFST members subjected to monotonic loading. As alluded in Section 1 of this paper, the fibre section cannot capture the development of local buckling of the steel tube. This indicates that the DP model may not be suitable for modelling CFST members subjected to cyclic loading, since there is significant strength deterioration caused by this phenomenon. To check the accuracy of the DP model under cyclic loading, specimen "CR-RuC15%-219-5-0%-C" [1] was modelled with the DP approach and the experimental and numerical responses are compared in Fig. 5. As one may infer, the DP model fails to predict strength deterioration as well as pinching effects, which proves that the DP approach is not suitable for simulating the flexural behaviour of CFST members under cyclic loading.

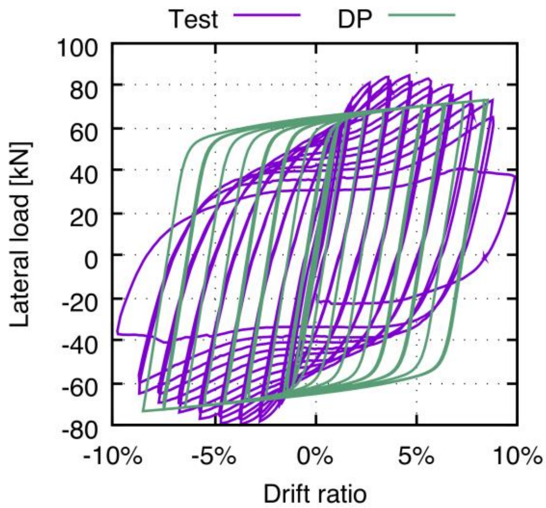


Fig. 5. Lateral load versus drift ratio comparison between test results and DP model prediction

3.2. Concentrated Plasticity model

The CP model is an alternative modelling approach that can be applied to CFST members. This model entails the modelling of rotational springs at the locations where plastic hinges are expected to occur. Thus, the model simplifies the plastic hinge zone to a nonlinear rotational spring, whilst the remaining portion of the element is assumed to remain elastic. As shown in Fig. 4, the model consists of one elastic beam-column element and two nonlinear rotational springs at the ends. The cyclic response of the CP model mainly depends on the hysteretic behaviour of the rotational spring. Therefore, it is necessary to adopt a suitable spring model to capture the cyclic flexural behaviour of the CFST member, especially in terms of strength deterioration and pinching effects. The modified Ibarra-Medina-Krawinkler deterioration model with peak-oriented hysteretic response (*ModIMKPeak-Oriented*), which was proposed by [7], was adopted as the rotational spring of the CP model. Fig. 6 shows the hysteretic response of the *ModIMKPeakOriented* model. It can be seen that the backbone curve of the model has a degradation stage after the peak load, which indicates that the model can simulate the strength deterioration of CFST member under cyclic loading. Differently from the DP model, building an accurate CP model cannot be attained without reliable response data, which accurately represents the seismic response of the the member being simulated.

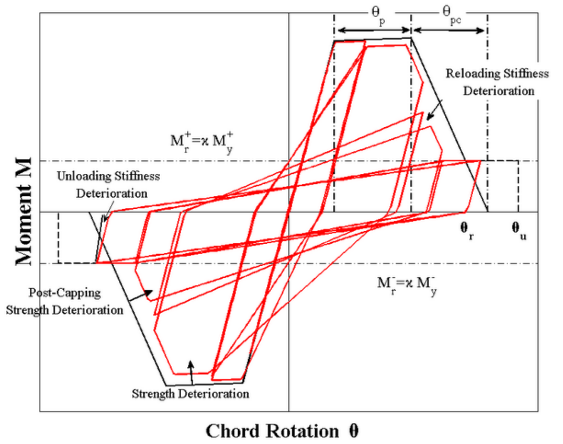


Fig. 6. ModIMKPeakOriented hysteretic model

Since the detailed FE model proved to be able to accurately simulate the cyclic flexural response of circular CFST members, the results obtained with such model were adopted as target data to calibrate the CP model. The parameters that define the *ModIMKPeakOriented* model can be divided into two groups, one group for the definition of the backbone curve and the other group for the control of the deterioration effects. As shown in Fig. 6, the backbone curve is defined as a tri-linear line with three data points which can be easily derived from the cyclic response data. Regarding the parameters to control the deterioration, no studies were yet conducted to determine a general rule for their definition in the context of CFST members. Thus, a reliable calibration framework is required to calibrate the deterioration parameters to match the base response. The CalTool [8], which makes use of the Harmony Search algorithm, was used for calibration purposes to obtain the set of parameters of the *ModIMKPeakOriented* model that leads to the best fit to the cyclic data derived with the 3D FE model.

To validate the accuracy of the *ModIMK-Peakriented* model, a circular CFST column, with steel grade S275 and concrete class C30/37, was selected and calibrated with the aforementioned optimization methods. The steel tube diameter and thickness were 244mm and 7mm, respectively. The cyclic flexural behaviour of the selected CFST column was obtained with the 3D FE model in ABAQUS subjected to the SAC loading protocol [9] without axial loading. Fig. 7 shows a comparison of moment-rotation curves between the 3D FE model and the calibrated CP model. It can be seen that the elastic stiffness and the backbone curve of the target data are well simulated by the *ModIMKPeakOriented* model, which means that the simplified model could capture the cyclic strength deterioration of the CFST member accurately. Howver, regarding the yield points on the unloading and reloading curves of each hysteretic cycle, the *ModIMK-PeakOriented* model always predicts lower values in comparison to the target data, which results in a conservative prediction of the energy dissipated in the CP model. Thus, to apply the *ModIMK-PeakOriented* model without any correction will lead to an inaccurate simulation of the cyclic flexural behaviour of a single CFST member.

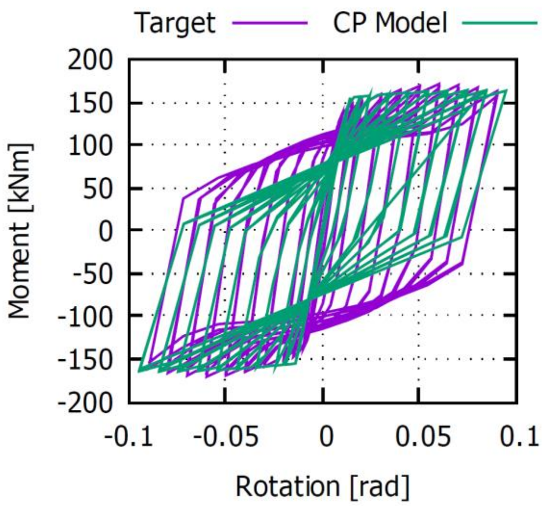


Fig. 7. Lateral load versus rotation comparison between the target data and the calibration results

To overcome the aforementioned limitation of the *ModIMKPeakOriented* model, an elastic rotational spring is introduced, as shown in Fig. 8. The main function of the elastic spring is to adjust the hysteretic rule of the *ModIMKPeakOriented* model. By taking advantage of the *Parallel Material* command in OpenSees [6], the elastic spring model is coupled with the *ModIMKPeakOriented* model with a combination factor of −1, which will make the elastic spring always have a weakening effect on the reaction moment of the *ModIMK-PeakOriented* model. Therefore, the unloading (reloading) yield points of the CP model will be shifted down (up) by the elastic spring.

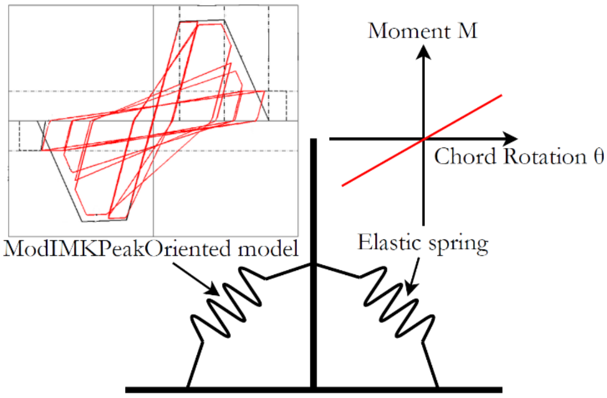


Fig. 8. The modified CP model proposed for a CFST member

The model, which combines the *ModIMKPeakOriented* model and elastic spring model, is designated by modified CP model in this paper. As the elastic spring model introduces a negative effect on the capacity of the CP model, the backbone curve of the *ModIMKPeak-Oriented* model needs to be corrected to make the backbone curve of the modified CP model similar to the backbone curve of the target data. To perform the correction, the backbone curve of the target data should be simplified to a tri-linear line, which is called the target backbone curve, as the black line shown in Fig. 9. The backbone curve of the *ModIMKPeakOriented* model is adopted as the summation of the target backbone curve (the black line of Fig. 9) and the elastic spring reaction curve (the green line of Fig. 9). It should be highlighted that as the elastic spring provides negative response to the *ModIMKPeakOriented* model, its reaction moments are plotted as negative values in Fig. 9. Regarding the stiffness of the elastic spring, its value could be adopted as the absolute slope rate of the line which connects the yield point of the unloading curve of the last cycle and the origin of the coordinate system.

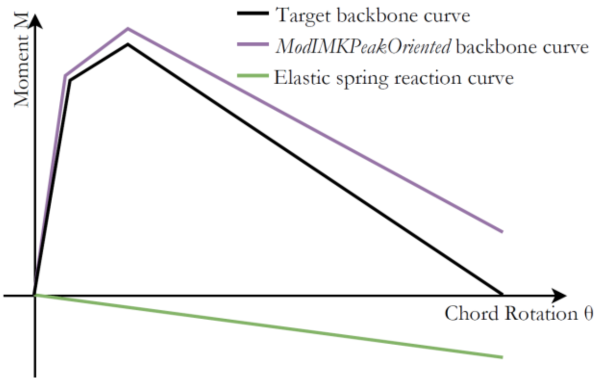


Fig. 9. Correction of the target backbone curve

To validate the accuracy of the modified CP model, the deterioration parameters of the previously described CFST member was re-calibrated with CalTool. Fig. 10 shows the moment-rotation plots of the data obtained with the 3D model and the calibrated results. It can be observed that with the employment of the elastic spring, the unloading/reloading curves of the calibrated hysteretic loops are in good agreement with the target curves. Overall, accuracy of the modified CP model is very good. Thus, it can be concluded that the modified CP model proposed in this work provides an higher degree of accuracy for the simulation of CFST members under cyclic loading in comparison to the reference model based on the *ModIMKPeak-Oriented* hysteretic model.

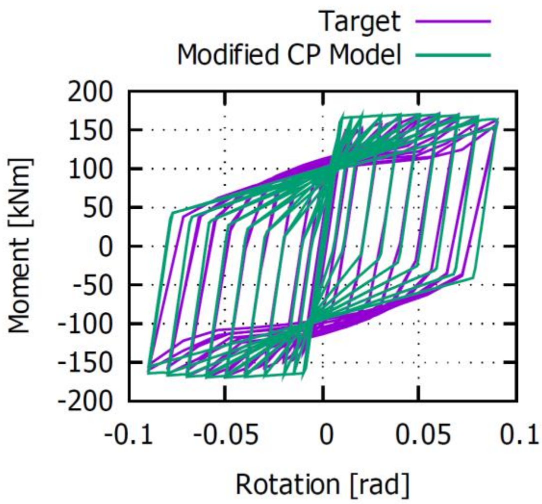


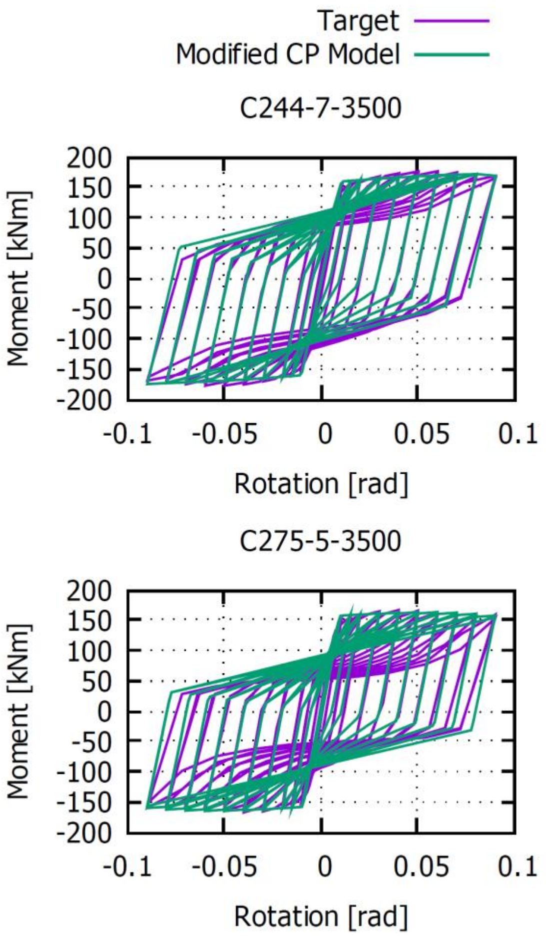
Fig. 10. Lateral load versus rotation comparison between the target data and the calibration results of the modified CP model

To further validate the feasibility of the modified CP model, three CFST members, which were extracted from the composite structure designed in [7], were selected. The details of the CFST members are listed in *Table 2*. All the CFST members share the same length $L = 1.75m$, the same concrete strength $f_c = 30MPa$ and the same steel grade, S275. It should be highlighted that, as the modified CP model cannot consider the axial load-moment interaction, different parameters were required for a CFST section under different axial load levels. In Fig. 11, the response obtained from the detailed FE model is compared with the response of the modified CP model with the optimized set of deterioration parameters. The CFST members were modelled in ABAQUS and subjected to the SAC loading protocol.

Table 2. CFST members used in the validation

CFST name	*D* [*mm*]	*t* [*mm*]	*P* [*kN*]
C244-7-3500	244	7	394
C273-5-3500	273	5	225
C323-5-3500	323	5	254

As demonstrated in Fig. 11, the modified CP model approach shows good agreement with the cyclic data obtained with ABAQUS. Differently from the DP model, the modified CP model also captures strength deterioration under cyclic loading, which is an essential aspect of the flexural response of CFST members.



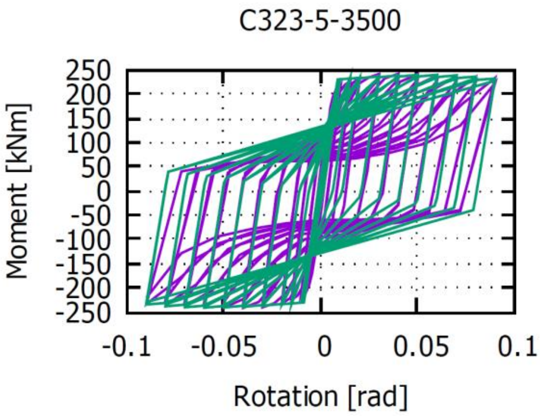


Fig. 11. Comparison between the ABAQUS cyclic response and the calibration results of the modified CP model

4. Conclusions

This paper focused on the proposal of a simplified numerical model for circular CFST members subjected to cyclic flexural loading. Based on experimental data, the feasibility of using detailed 3D FE model, distributed plasticity (DP) models and concentrated plasticity (CP) models was discussed. Regarding the latter, two rotational spring models and one calibration tool were used to find the optimum set of deterioration parameters. The accuracy of the calibrated CP model was verified by comparing the response data obtained with a 3D ABAQUS model and the calibrated results. From the results obtained, the following conclusions can be extracted:

- The 3D FE model can provide an accurate prediction of the monotonic/cyclic flexural response of CFST member. However, this comes at a high computational cost that restricts its use for large-scale simulations (e.g. frame-level analysis)
- The DP model fails to simulate with accuracy the cyclic behaviour of CFST members, as it lacks the ability to capture, amongst other phenomena, the development of local buckling mechanisms. Since this phenomenon plays an important role on the cyclic flexural response of these members, it becomes clear that it is not suitable for numerical simulations of CFST members subjected to cyclic loading conditions.
- The use of a CP modelling approach consisting of the combination of two springs in parallel based, coupled with an efficient calibration framework, reveals to be an

efficient option for the simplified numerical simulation of the cyclic flexural response of circular CFST members.

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