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The Cyclic Behavior of I-Shaped Steel Deep Beams Reinforced with CFRP

Anis Mohabeddine, Cyrus Eshaghi, José Correia, and José Miguel Castro

Abstract This paper presents the flexural cyclic behavior of I-shaped hot rolled steel deep sections used as beams in moment-resisting frames (MRF) featuring a carbon fiber reinforced polymer (CFRP) patch on the web through advanced finite element analysis. The main goal of the CFRP reinforcement is to increase the rotation capacity of the member without increasing the overstrength to avoid compromising the strong column-weak beam condition in MRF. A reduced finite element model of a steel beam is developed and validated with experimental data. The CFRP patch is modeled considering fracture in the adhesive layer using the cohesive zone modeling (CZM) technique that can capture the crack initiation and propagation. Different adhesive types are investigated where the CZM parameters are calibrated from high fidelity fracture mechanics tests that are thoroughly validated in the literature. This includes a rigid adhesive commonly found in the construction industry and two tough adhesives used in the automotive industry. The results revealed that the CFRP patch can increase the rotation capacity of a steel member considerably when using tough adhesives.

Keywords CFRP · Cyclic · Rotation Capacity · Seismic Moment Resisting Frames · Steel

A. Mohabeddine (✉) · J. M. Castro
Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
e-mail: a.i.mohabeddine@tudelft.nl

J. M. Castro
e-mail: jmcastro@fe.up.pt

A. Mohabeddine · C. Eshaghi
CONSTRUCT, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal
e-mail: up202010595@edu.fe.up.pt

J. Correia
INEGI and CONSTRUCT, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal
e-mail: jacorreia@fe.up.pt

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1 Introduction

High ductility class hot-rolled steel profiles (i.e. class 1) according to Eurocode 3 are able to develop large plastic deformation before significant loss of strength under monotonic lateral loading [1]. However, recent research studies showed that this is not necessarily the case when they are subjected to cyclic loading [1, 2]. Araujo et al. [3] reported that the deformation capacity of steel members under cyclic loading is around 30% of the capacity under monotonic loading. Several researches [3, 4] reported that deep steel wide flange sections achieve limited rotation capacity where some of them do not reach the minimum requirement specified in AISC341-16 [5] for highly ductile connections. The poor performance of some deep I-shaped sections commonly used in practice may raise a strong need for retrofitting of existing buildings. Thus, the development of new reinforcement methods to increase the rotation capacity of existing steel members of MRF is of paramount interest.

The use of bonded fiber-reinforced polymers (FRP) is well established for the seismic retrofitting of concrete and masonry structures. However, there is limited information about how they can be used to strengthen steel structures [6]. There is a great research interest in using FRP for strengthening bridge girders and enhancing the fatigue performance of the structural components [7–9]. However, few studies focused on the effectiveness of the application of FRP to enhance the stability of members in the context of seismic design. El-Tawil et al. [1] tested steel double-channel built-up members subjected to flexural cyclic loading, where some of them were wrapped with CFRP in the plastic hinge region. The results demonstrated that the CFRP could increase the size of the plastic hinge and delay the occurrence of local buckling as well as lateral and torsional buckling. The drift at peak strength could be increased from 4.4 to 6.6%. Harries et al. [2] tested W-T steel specimens with stocky flanges and slender web retrofitted with GFRP subjected to monotonic and cyclic loading. The results revealed that the FRP controlled the web buckling, inhibited the formation of plastic kinking, and allowed the member to withstand a greater amount of monotonic and cyclic loading.

Mohabeddine et al. [9] showed that web slenderness plays an important role in the deformation capacity of steel members with deep section (i.e., $h/b_f \geq 2$, where h is the section height and b_f is the flange width). Strengthening with bonded CFRP will share tension stresses thus reducing cumulative tensile plastic deformation and counteract plate bending deformation on the compressed plates caused by local buckling. Thus, it will delay the accumulation of plastic damage in every excursion imposed by the loading protocol which will potentially increase the rotation capacity. The effectiveness of this retrofitting technique will depend strongly on the adhesive strength and ductility which will determine at which stage of the cyclic loading, CFRP debonding will occur.

This paper investigates the effectiveness of the application of CFRP in enhancing the rotation capacity of deep steel beams by bonding CFRP on the web. A finite element model is developed in the commercial software ABAQUS. The model consists of a cantilever beam that represents the behavior of beams in MRF with length corresponding to the distance between the fixed end and the inflection point. Nonlinear geometrical instabilities, as well as the material nonlinear cyclic behavior of structural steel, are considered in the model. Debonding failure of the adhesive joint is simulated through the use of a cohesive zone model with traction separation law which simulates the elastic behavior, the damage initiation, and the evolution of damage through a softening behavior until reaching the complete separation of the adherend. Different adhesive types featuring different fracture properties are investigated. Finally, the cyclic behavior of the unreinforced control beam and CFRP retrofitted steel beams are compared.

2 Methodology

The purpose of this study is to investigate the cyclic behavior of steel I shaped flexural member reinforced with CFRP. Therefore, a high fidelity finite element model is developed in ABAQUS and subjected to symmetric cyclic lateral loading (i.e. SAC protocol). The model consists of a cantilever beam that is assumed to reproduce the behavior of the beam from one end to the point of inflection, which is assumed to be located at the mid-length of the beam.

The control unreinforced steel beam is an European IPE 400 profile with length $L = 1.35$, as presented in Fig. 1(a). One edge is fully restrained in the 6 degrees of freedom to ensure the fixed boundary conditions. The cyclic loading is applied on the other edge of the beam, which is restrained in the X-X direction to avoid out-of-plane displacements at the top of the specimen. Except for the CFRP patch, the reinforced beam, shown in Fig. 1(b), has the same geometrical and mechanical properties as the unreinforced one. CFRP patches are bonded on both sides of the web in the plastic hinge region. The dimensions of the CFRP patch are 400 $\times$ 150 $\times$ 3 mm. This length is taken to ensure that the CFRP will cover the full plastic hinge region.

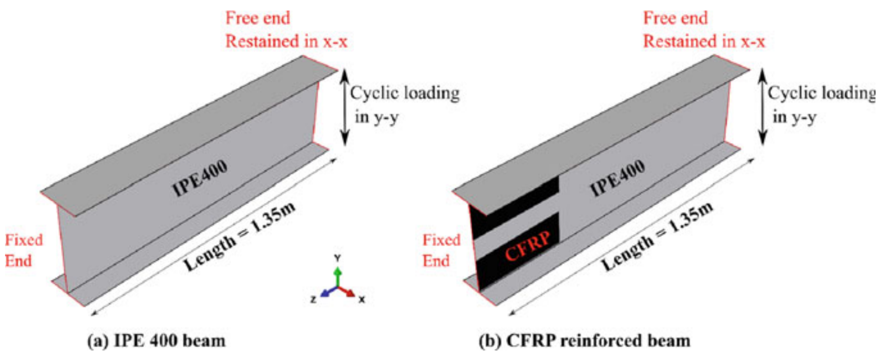


Fig. 1 Beam model with and without CFRP reinforcement

The performance of the CFRP patch will depend strongly on the mechanical properties of the adhesives used for bonding. In this study, the influence of three different epoxy structural adhesives is investigated. The adhesives used are:

SIKADUR30: produced by SIKA® to be used for CFRP reinforcement in the construction industry. It is a rigid high strength structural adhesive commonly used in research related to the construction industry for concrete and metallic structures [10].
AF 163 2 K: produced by 3M Scotch Weld. A high strength ductile adhesive used in the automotive industry [11].
Nagase Denatite XNR6852E-3: produced by Nagase ChemteX® (Osaka, Japan). A crash-resistant, tough epoxy adhesive, which is distinguished by its high strength, ductility, and resistance to impact. It can deform significantly before failure, allowing the bonded structure to deform plastically and to absorb the impact energy.

2.1 Finite Element Modelling

2.1.1 Control Beam Without CFRP Reinforcement

A Finite element model was developed in the commercial software ABAQUS which was used by the authors in a previous related study [2]. The beam plates are modelled using quadratic shell elements S4R with five Gauss integration points. After a mesh sensitivity study, the mesh size adopted is equal to $b_f/12 = 15$ mm, where b_f is the flange width. The length of the cantilever beam is taken as 1.35 m, which corresponds to specimens of a future experimental campaign that will be conducted by the authors. Flange and web imperfections are included in the model considering the manufacturer's shape tolerances according to EN10034 [12]. The web imperfection is considered by adopting a bow shape having a maximum amplitude at the mid-depth to $h/250$, where h is the section height, and symmetric out of squareness flanges with a deviation for both flanges equal to $b_f/250$. The combined nonlinear isotropic/kinematic cyclic plasticity material model available in the ABAQUS materials library is adopted to capture the complex cyclic behavior of the material. More information can be found in [2, 13]. The finite element model is validated with experimental data from the literature, as shown in Fig. 2. More information can be found in [2].

2.1.2 Beam with CFRP Reinforcement

Unidirectional pultruded S&P C- Laminate HM produced by the S&P reinforcement [14] are adopted in this study. The CFRP was modelled as an orthotropic elastic shell. The adhesive layer between the CFRP and the steel substrate was modelled using the cohesive zone modelling approach (CZM), which is the most widely used

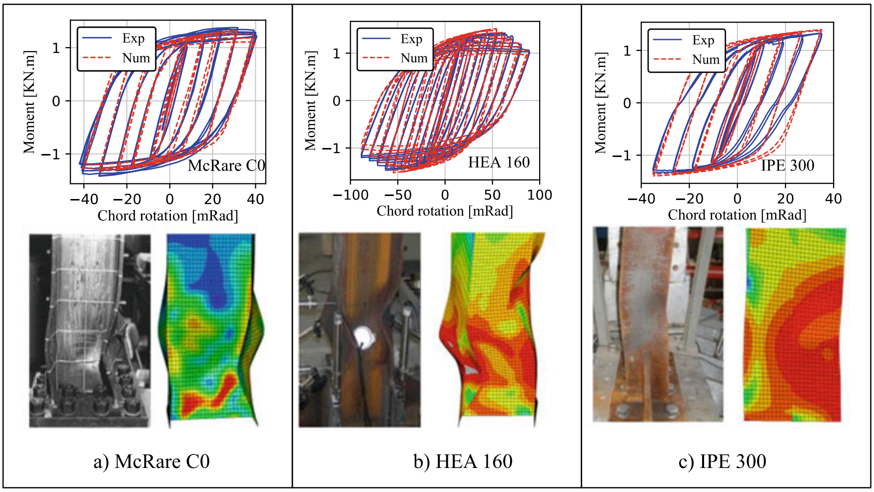


Fig. 2 Validation of the finite element model with experimental results [2]

method to simulate the interfacial fracture in the adhesive layer [15]. The properties of the adhesives were obtained by comprehensive experimental testing and numerical validations [10, 16]. More details about the modelling the adhesive layer can be found in ref. [17].

3 Results and Discussion

Figure 3 shows the comparison between the buckling behavior of the bare steel beam and the CFRP reinforced beam (with AF 163-2K adhesive) at the second cycle of 40 mrad rotation imposed cyclic loading where both of them experienced local buckling and strength deterioration. The bare steel beam experienced flange and web local buckling combined with limited lateral and torsional buckling that can be observed from the non-uniform distribution of stress outside the plastic hinge region which clearly indicates out of plane bending. The CFRP reinforced beam experienced significant debonding of CFRP in the plastic region where at this stage it became ineffective since it is not bonded in the buckled region. The CFRP reinforced beam exhibits only flange and web local buckling with a more uniform stress distribution and longer plastic hinge. The CFRP prevented the lateral and torsional buckling at this level of demands. It is worth noting that this has been also observed by El-Tawil et al. [18] in physical tests conducted on double channel built-up members wrapped with CFRP in the plastic hinge region.

Figure 4 shows the moment-chord rotation curves and the first cycle backbone curve for bare steel beams and retrofitted ones. The chord rotation is equal to the imposed lateral displacement in the free end of the beam divided by the length.

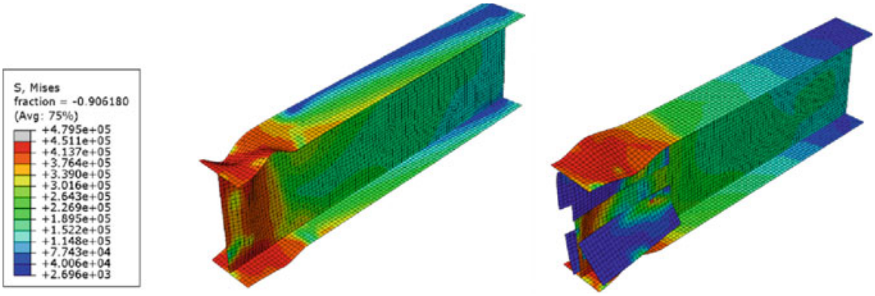
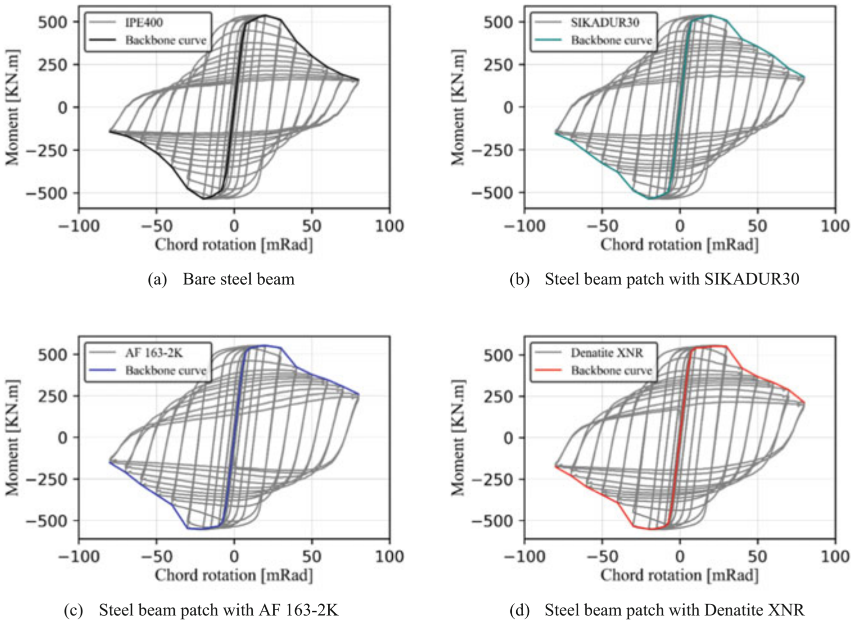


Fig. 3 Buckling behavior of a bare steel beam and a CFRP reinforced beam (Unit kPa)

The moment-chord rotation hysteresis curves of the three reinforced steel beams are wider than the control steel beam. This clearly indicates that the CFRP contributes to higher energy dissipation, which is strongly desired in seismic design. Figure 5(a–b) compare the positive and negative first cycle backbone curves of the control beam and the CFRP reinforced ones. As expected, the application of the CFRP did not increase the bending strength of the member which is very important as it would not compromise the weak beam-strong column condition in a steel MRF. The beam reinforced with rigid adhesive SIKADUR30 did not improve the cyclic performance considerably. It reached the same rotation at peak bending moment and failed at the same residual strength. However, the reinforced beam with SIKADUR30 benefited from a slightly lower strength deterioration rate as the post peak strength between $40\,\text{mrad} \leq \theta < 80\,\text{mRad}$ is higher than the control beam for both the negative and positive backbone curves. The beams reinforced using tough adhesives (i.e. AF 163 3K and Denatite XNR 6852E-3) exhibited an important enhancement of the behavior with an increase of 10 mrad at peak moment, a lower strength deterioration and higher residual strength. Although this improvement may not seem significant, 10 mrad of additional plastic rotation at peak moment can have a significant influence on the overall behavior of a steel moment-resisting framed structure. Besides, in the case of in a full-strength rigid MRF connections, by assuming that the components other than the beam have a negligible deformation, the enhancement obtained by using CFRP can shift the classification of the connection from moderately ductile to highly ductile qualified connection to be used for seismic design. For instance, AISC 341-16 [5] requires a chord rotation of 40 mRad at post peak strength of 80% yield moment (My). The unreinforced beam barely achieves this limit in the positive backbone curve shown in Fig. 5 (a) and does not reach it in the negative backbone curve as shown in Fig. 5(b). Whereas the reinforced beams achieved both in the positive and negative backbone curves.

Figure 6 presents the comparison of the cohesive behavior of the reinforced beams bonded with the three different adhesives considered in this study. For this purpose, the CSDMG parameter, which is a ratio that represents the damage state of the adhesive layer, is adopted, where 0 indicates an undamaged adhesive layer and 1 a fully debonded adhesive layer. In the three cases, the damage started at very early



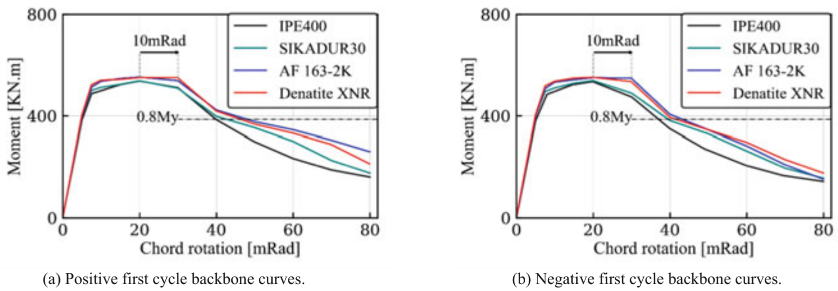
(a) Bare steel beam

(b) Steel beam patch with SIKADUR30

(c) Steel beam patch with AF 163-2K

(d) Steel beam patch with Denatite XNR

Fig. 4 Moment rotation cyclic curves and first cycle backbone curves



(a) Positive first cycle backbone curves.

(b) Negative first cycle backbone curves.

Fig. 5 Comparison between the bare steel beam and reinforced ones

stages (5 mrad) at the free ends of the CFRP. This is a very common issue in adhesively bonded joints where high peeling stress develops at the free ends.

The CFRP patched with the rigid adhesive SIKADUR30 reached more than 90% of damage at very early stages of the loading (i.e. 10 mrad). This is the main reason that justifies the limited improvement of the cyclic performance observed in the previous section. In the case of the AF 163 2K adhesive, the damage initiated from the free ends and propagated towards the buckled region. Significant debonding started at 30 mrad and complete debonding in the buckled region occurred at 40 mrad. Similar

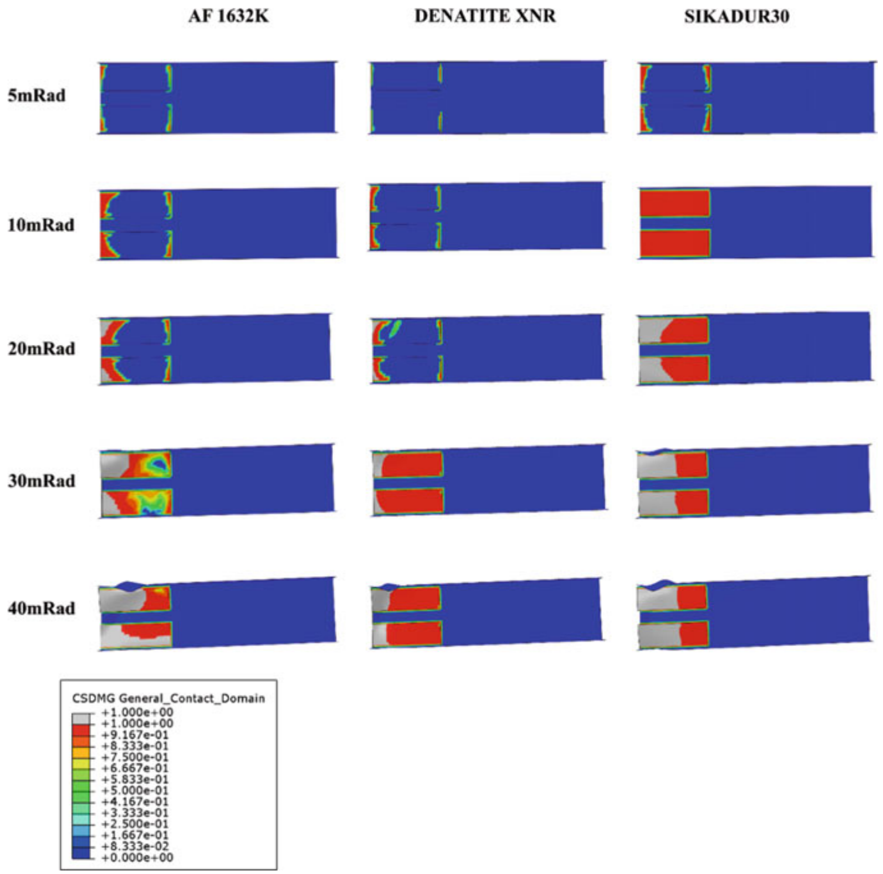


Fig. 6 Comparison between the CZM behavior of a tough adhesives (AF 1632K and DENATITE XNR) and a rigid adhesive (SIKADUR30)

behavior was observed with the other tough adhesive DENATITE XNR but with lower damage level since it is much tougher than the AF 163 2K.

4 Conclusions

This paper investigated the cyclic performance of I shaped beams patched in the web with CFRP using high fidelity finite element analysis. The modelling methodology of the CFRP patch using cohesive zone modelling approach is thoroughly detailed which can be useful for future research related to civil engineering structures since these methods are typically used in research in the automotive and aerospace industries.

The main conclusion and recommendations can be summarized as follows:

(a) The beneficial effect of the CFRP patch was clearly evident in several aspects such as the enlarged hysteresis curves, elongated plastic hinge region, and the increased the rotation capacity.
(b) It is clear that the use of tough adhesive is inevitable for seismic design applications where large plastic deformations are involved. The adoption of rigid adhesives commonly used in construction practice does not provide any significant benefits in what concerns increase in the deformation capacity of steel members.
(c) Debonding started in the free edges early stages, thus techniques for reducing the peeling stress such as tapering the CFRP, or applying some compressive stress with clamps should be considered in future research studies.
(d) The difference between the two tough adhesives could not be clearly observed. This is mainly due to the high plastic deformation experienced by the web. However, the use triangular TLS is conservative for tough adhesives used in this study, other more adapted models such as the trapezoidal will provide a higher performance of the adhesive.

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