

Numerical Assessment of the Cyclic Response of Aluminium Beams Using OpenSees[†]

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Abstract

Aluminium alloys are increasingly adopted in structural engineering due to their favourable strength-to-weight ratio, durability against corrosion, and sustainability benefits. This paper examines the cyclic response of hollow section beams manufactured from 6082-T6 aluminium alloy through a combined numerical–experimental approach. Based on experimental results available in the literature concerning aluminium beams subjected to incremental cyclic bending, an efficient computational model is developed within the OpenSees framework to reproduce cyclic hardening and low-cycle fatigue. The modelling strategy integrates the Giuffrè–Menegotto–Pinto constitutive law with a fatigue material formulation. Model parameters are calibrated against experimental force–displacement responses and cumulative dissipated energy to ensure an accurate representation of observed behaviour. The numerical results show good agreement with experimental data, successfully reproducing both the global cyclic response and material degradation phenomena.

Keywords: aluminium beams; cyclic loading; OpenSees modeling

1. Introduction

In recent decades, aluminium alloys have gained increasing attention in structural engineering owing to their favourable properties, such as a high strength-to-weight ratio, excellent corrosion resistance, and good recyclability. These characteristics make aluminium particularly suitable for applications including lightweight structures, offshore systems, and movable bridges [1–3]. However, compared to steel, aluminium exhibits a lower elastic modulus, which makes structural members more susceptible to instability phenomena, particularly local buckling, and thus requires careful consideration in design [4–7]. Furthermore, the mechanical behaviour of aluminium alloys is characterised by pronounced strain hardening and sensitivity to cyclic loading. While their response under monotonic loading has been extensively investigated, studies addressing cyclic behaviour remain relatively limited, especially at the structural member level. Most of the available research has focused on material characterisation, including hysteretic response and low-cycle fatigue behaviour of 6xxx and 7xxx series alloys. Among these contributions, the experimental campaign by Pisapia et al. [8] provided a comprehensive investigation of 5xxx, 6xxx, and



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7xxx series alloys through monotonic, cyclic, and low-cycle fatigue tests, highlighting key aspects such as cyclic hardening, energy dissipation, and plastic fracture mechanisms. Recently, Georgantzia et al. [9] performed cyclic tests on coupons made from 6082-T6, 6063-T6 and 6060-T5 aluminium alloys up to 6.5% strain amplitude. This study was followed by low-cycle, high-amplitude fatigue tests providing valuable experimental evidence on fatigue life and enabling the calibration of low-cycle fatigue models [10]. Despite these efforts, current design standards, such as EN 1999-1-1 [11], primarily address static loading conditions, with limited provisions for cyclic or seismic applications. Although recent developments within the second generation of Eurocodes [12] have begun to incorporate aluminium structures, further research is still required to improve the understanding and prediction of their cyclic response, particularly with regard to damage accumulation and failure mechanisms.

Within this context, the present study develops and calibrates a numerical model for aluminium hollow section beams subjected to low-cycle fatigue within the OpenSees framework. The proposed approach aims to provide an efficient and reliable tool for simulating the hysteretic response and fatigue-induced failure of aluminium members under cyclic loading. In contrast to the preliminary model presented in Maglio et al. [13], which addressed 6060-T6 SHS members affected by local-instability-related degradation, the present study considers two Class 1–2 6082-T6 sections from a separate experimental campaign, explicitly evaluates the plastic-hinge length, and applies the fatigue formulation to the complete cross-section to reproduce abrupt material fracture.

2. Reference Experimental Campaign

The present work builds upon the experimental programme conducted by Georgantzia et al. [14] which involved eight hollow and concrete-filled aluminium beams fabricated from two alloys, 6082-T6 and 6063-T6, and subjected to cyclic loading. Since the objective of this study is to calibrate a numerical model capable of accurately predicting the behaviour of aluminium beams that can achieve their full flexural capacity, and are therefore not affected by local buckling, only hollow section beams $H152.4 \times 50.8 \times 6.35$ and $H101.6 \times 101.6 \times 6.35$ were selected. Table 1 summarises the main characteristics of the selected specimens, where, according to Figure 1b, D denotes the outer depth, B the outer width, t the wall thickness, and L the specimen length, together with the cross-sectional class determined according to EN 1999-1-1 [11].

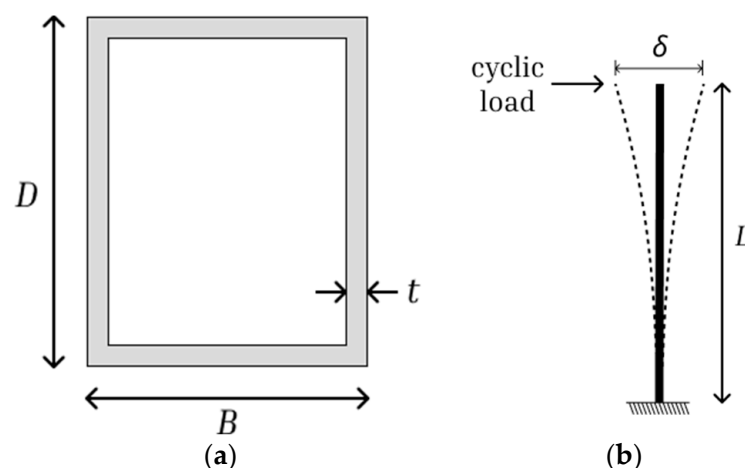


Figure 1. Cross-section geometry (a) and scheme of loading setup (b).

A schematic representation of the loading setup adopted in the experimental tests is shown in Figure 1b.

Table 1. Summary of main properties of selected specimens.

Specimen ID	<i>D</i> (mm)	<i>B</i> (mm)	<i>t</i> (mm)	EN 1991-1-1 Class [11]	<i>L</i>	Alloy
H152.4 × 50.8 × 6.35	152.20	50.50	6.33	1	1080	6082-T6
H101.6 × 101.6 × 6.35	101.20	99.80	6.32	2	1040	6082-T6

3. Numerical Model

The computational framework OpenSees is employed in this study to develop an efficient numerical model of aluminium hollow sections, capable of capturing the inelastic hysteretic response while accounting for damage induced by cyclic loading. A distributed plasticity formulation is adopted to represent regions subjected to inelastic strains, as discussed in the following sections. A key limitation of this approach in OpenSees lies in the assumption that plane sections remain plane; consequently, section distortion and local buckling cannot be directly captured. In a previous study by the authors [13], cyclic damage associated with local buckling in slender sections was simulated through appropriate cross-sectional mesh refinement combined with a fatigue material model. However, in the present work, the cross-sections considered in the experimental programme belong to Class 1 and Class 2 according to EN 1999-1-1 [15]; therefore, local buckling is not expected to significantly affect the response, and failure is primarily governed by material fracture following cyclic yielding.

The calibration of the numerical model is performed in two sequential phases. The first phase aims to reproduce the cyclic response of the beams up to the onset of damage, through appropriate calibration of the material parameters and the length of the inelastic region where plastic hinges develop. The second phase focuses on modelling damage due to low-cycle fatigue by employing the fatigue material model available in OpenSees.

3.1. Material Model

The Giuffrè–Menegotto–Pinto material model [16] was adopted for the nonlinear beam–column elements. This model, implemented in the OpenSees framework as Steel02 command [15], is capable of accurately predicting the nonlinear behaviour of ductile metallic materials under both monotonic and cyclic loading, as it accounts for yielding and the Bauschinger effect, as well as kinematic and isotropic hardening. Table 2 provides the time-invariant material parameters adopted by Maglio et al. [13]. In particular E_0 is the initial Young’s modulus, σ_y is the conventional yield stress, b is the strain-hardening ratio, R_0 is the initial curvature between the elastic and post-yield slopes, cR_1 and cR_2 are parameters to control the Bauschinger curvature after each strain reversal and α_1 , α_2 , α_3 , and α_4 are the isotropic hardening parameters in compression and tension respectively.

Table 2. Parameters of Steel02 material model adopted from [13].

Alloy	E_0 (MPa)	σ_y (MPa)	b	R_0	cR_1	cR_2	α_1	α_2	α_3	α_4
6082-T6	67,653	299.3	0.005	7.5	0.6	0.15	0.08	1.0	0.08	1.0

3.2. Model Calibration Without Damage

As previously mentioned, the first stage aims to define an optimised numerical model capable of accurately reproducing the cyclic hardening response observed in the experimental tests, up to the maximum strength, as represented by the continuous curves in Figure 2a,b for the considered specimens. Figure 2c provides a schematic overview of the numerical model implemented in OpenSees.

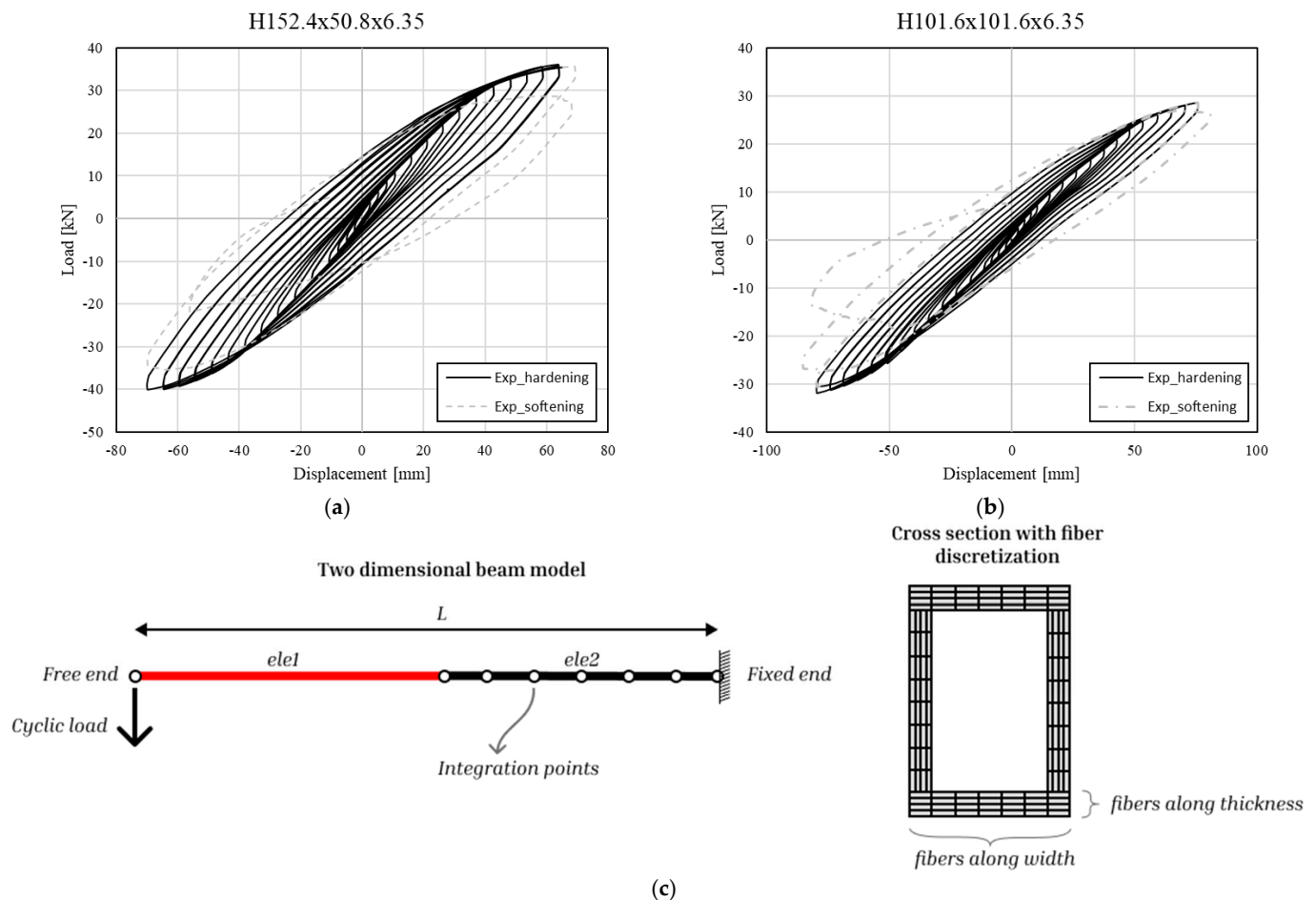


Figure 2. Experimental curve for H152.4 × 50.8 × 6.35 specimen (a) and H101.6 × 101.6 × 6.35 specimen (b) (Experimental data adapted from [14]); numerical scheme model (c).

The two-dimensional beam model is discretised into two elements: an elastic beam element and a fibre-based nonlinear beam–column element, denoted as ele1 and ele2, respectively. To replicate the experimental boundary conditions, one end of the beam is restrained against all translational degrees of freedom, while the opposite end, where the load is applied, is left free. Based on previous numerical analyses [13], the cross-section of the nonlinear element was discretised into four fibres through the thickness and 20 fibres along the width of each plate, with the number of integration points set to seven.

To define the plastic hinge region (nonlinear beam–column element), three different approaches were used to calculate the corresponding length: (i) the experimentally measured plastic hinge length $L_{pl.mes}$ [14], (ii) the theoretically estimated plastic hinge length $L_{pl.th}$, defined in Equation (1) where W_{pl} and W_{el} are the plastic and elastic moduli of the cross-section respectively, and (iii) the plastic hinge length proposed in [17], $L_{pl.sl} = \alpha L_v$, expressed as a function of the shear length L_v , where the coefficient α is set equal to 0.22.

$$L_{pl.th} = \frac{(W_{pl} - W_{el})}{W_{pl}} \cdot L \quad (1)$$

The computed values are summarised in Table 3. It can be observed that the three plastic hinge length estimates are very similar for the H152.4 × 50.8 × 6.35 specimen, whereas greater discrepancies are found for the square hollow section. Figure 3a illustrates, for the case of the H152.4 × 50.8 × 6.35 specimen, the comparison between the experimental responses and the corresponding numerical predictions obtained by adopting the plastic

hinge lengths reported in Table 3. The results show that no significant differences are observed among the various assumptions. Furthermore, to assess the influence of a shorter plastic hinge length, an additional model with a hinge length of 100 mm is included in Figure 3b. It is evident that a length of the fibre-based beam element shorter than that reported in Table 3 is not sufficient to accurately capture the nonlinear behaviour of the beam. Based on these observations, Equation (1) is selected as the most suitable expression for defining the plastic hinge length in the subsequent analyses.

Table 3. Tested values of plastic hinge length.

Specimen	$L_{pl.mes}$ [mm]	$L_{pl.th}$ [mm]	$L_{pl.sl}$ [mm]
H152.4 × 50.8 × 6.35	203	236	237
H101.6 × 101.6 × 6.35	143	170	228

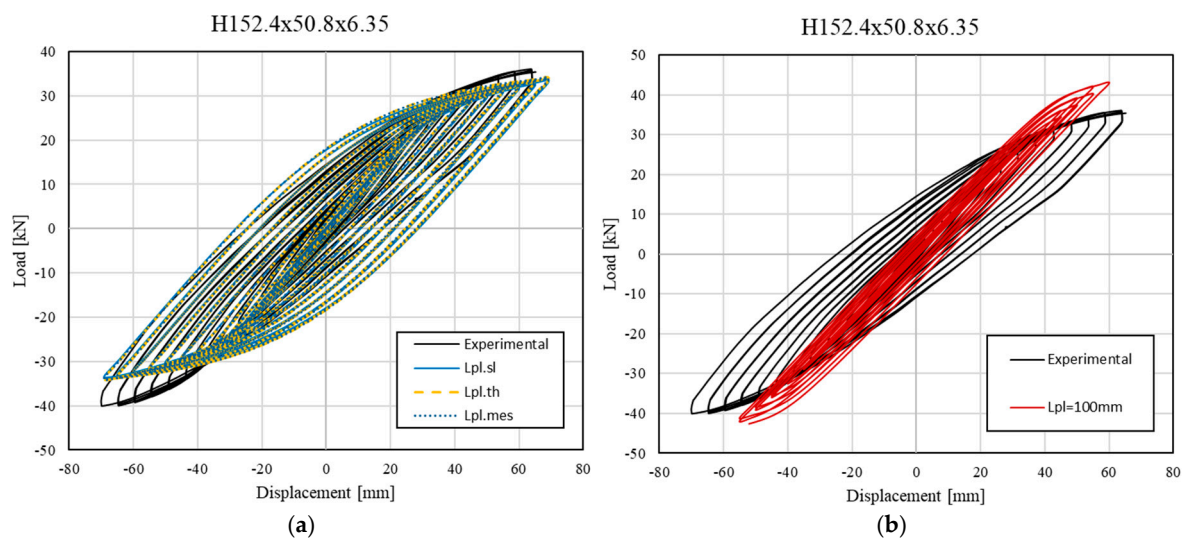


Figure 3. Comparison of numerical and experimental curves adopting the plastic hinge lengths reported in Table 3 (a), and a plastic hinge length equal to 100 mm (b).

3.3. Damage Model Calibration

To account for the failure mechanism associated with low-cycle fatigue, the Fatigue material command available in OpenSees was adopted. This formulation predicts cumulative damage according to a linear strain accumulation model based on Miner's rule, while incorporating a modified rainflow cycle-counting algorithm [18] which tracks only the four most recent strain reversal peaks at each time increment. The Fatigue material is implemented in parallel with Steel02, acting as a wrapper around the base material. It does not influence the stress–strain response until the damage index in a fibre reaches a value of 1.0, at which point the stress in that fibre is reduced to zero, simulating fracture. The fatigue life is evaluated based on the linear relationship proposed by Manson and Coffin [19,20], expressed in logarithmic form between the plastic strain amplitude, ε_i , and the number of cycles to failure, N_f , as:

$$\varepsilon_i = \varepsilon_0 (N_f)^m \quad (2)$$

where ε_0 (fatigue ductility coefficient) represents the plastic strain level at which a single cycle causes failure, and m (fatigue ductility exponent) defines the slope of the linear relationship. Since the experimental specimens exhibited a sudden failure in the last cycles without noticeable gradual strength degradation, the fatigue material was assigned to the entire cross-section. This approach differs from the authors' previous work [13], where the

fatigue model was applied only to a calibrated portion of the cross-section to account for gradual cyclic degradation induced by local instability.

The calibrated fatigue parameters are $\varepsilon_0 = 0.168$ and $m = -0.67$ for the $H152.4 \times 50.8 \times 6.35$ specimen, and $\varepsilon_0 = 0.168$ and $m = -0.738$ for the $H101.6 \times 101.6 \times 6.35$ specimen. Figure 4 compares the experimental results with the corresponding numerical predictions. Overall, good agreement is observed for both specimens. The only noticeable discrepancy is associated with the slight asymmetry in the negative loading branch of the experimental response for both specimens, which cannot be reproduced by the proposed beam model. The asymmetry in the experimental results may be attributed to the base connection not behaving as a perfect fixed-end support under both loading directions, as also reported by the author in the original paper [14]. Given that the numerical prediction is on the conservative side, attempting to model this asymmetry would excessively complicate the numerical code, undermining its advantage in terms of ease of use and computational efficiency for future parametric analyses.

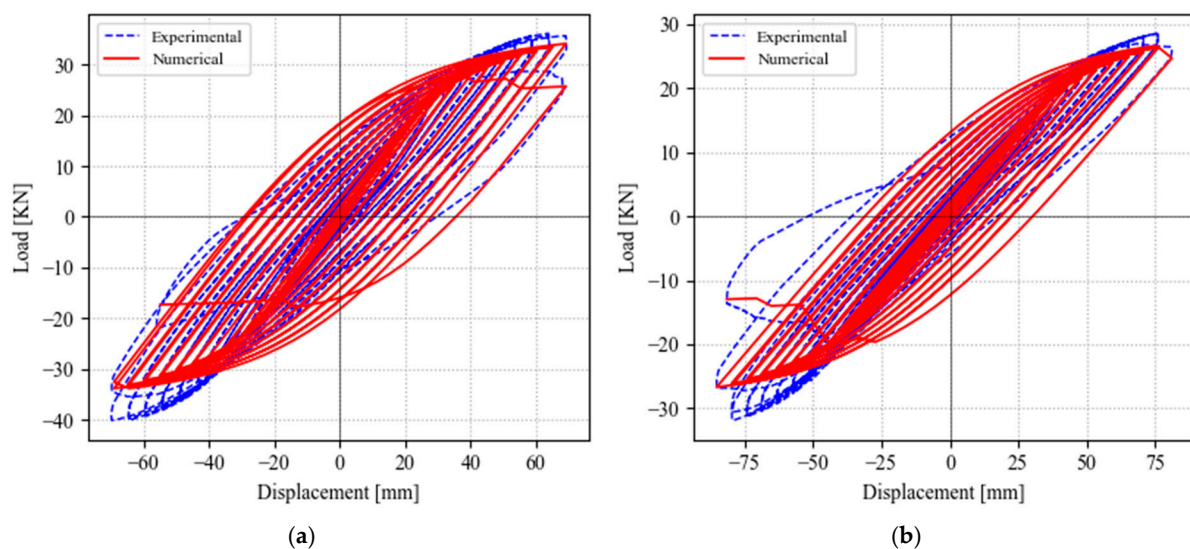


Figure 4. Comparison between experimental and numerical simulation for $H152.4 \times 50.8 \times 6.35$ specimen (a) and for $H101.6 \times 101.6 \times 6.35$ specimen (b).

4. Conclusions

This study presented the development and calibration of a numerical model for aluminium hollow section beams subjected to cyclic loading, with a particular focus on low-cycle fatigue behaviour. The model was implemented in the OpenSees framework using a distributed plasticity approach combined with a fatigue damage formulation. Based on the results obtained, the following conclusions can be drawn:

The adopted modelling strategy, based on fibre-based beam-column elements and the Giuffrè–Menegotto–Pinto material model (Steel02), proved capable of accurately reproducing the cyclic hardening response of aluminium beams up to the onset of damage.

The fatigue material model available in OpenSees, based on Miner’s rule and the Coffin–Manson relationship, was successfully calibrated to simulate failure due to low-cycle fatigue. The adopted approach was able to capture the abrupt fracture observed experimentally, without requiring gradual stiffness or strength degradation.

The numerical results showed good agreement with the experimental responses for both investigated specimens, confirming the capability of the proposed model to predict both the hysteretic behaviour and the fatigue-induced failure.

The main limitation of the adopted modelling approach is related to the assumption that plane sections remain plane, which prevents the direct simulation of local buckling and cross-sectional distortion. However, this limitation is not critical for the analysed cases, as the selected cross-sections belong to Class 1 and Class 2, where failure is governed by material fracture rather than instability phenomena.

Overall, the proposed modelling framework represents an efficient and reliable tool for the simulation of aluminium structural members under cyclic loading. Future developments will focus on extending the approach to slender sections, where the interaction between local buckling and fatigue damage plays a significant role.

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