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Comparative analysis of cyclic models for steel beams

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ABSTRACT

Phenomenological models are used to simulate post-elastic behaviour of steel beams in the framework of concentrated plasticity. Many of them can model degradation phenomena occurring during cyclic loading, but these are often governed by model parameters without clear physical meaning. It follows that in this case parameter calibration must be performed by curve fitting of experimental responses.
In this work, several numerical models (simple hysteretic, modified Ibarra-Medina-Krawinkler, Bouc-Wen and Sivaselvan-Reinhorn), implemented in widely used software packages, are calibrated against the results provided by an experimental programme involving cyclic and monotonic tests on open and closed cross-section beams, by employing a multi-objective optimisation methodology recently developed by the authors. The extensive calibration analyses carried out show that the most accurate model among those investigated is the Sivalselvan-Reinhorn model, which is able to provide realistic simulations of both monotonic and cyclic responses. Extension of the calibration procedure is proposed, which considers an additional objective related to the envelope curve of the cyclic response, and it is shown that this improvement adds robustness to the results. Finally, a preliminary regression analysis of the results, aimed at correlating degradation model parameters to geometric and mechanical properties of the member, is described.

1. Introduction

Beam-to-column joints represent critical components for the structural behaviour of moment resisting steel frames. According to Eurocode 3 [1], depending on the relative stiffness and strength of the members and the connection, beam-to-column joints may be respectively classified as rigid/semi-rigid/pinned joints and full-/partial-strength joints. Additionally, further classification based on plastic rotation supply has been proposed by other authors [2], in which the joints are divided into full- and partial-ductility. In the case of full-strength joints, the cyclic behaviour in terms of post-elastic regime, dissipated energy, stiffness and strength degradation, is governed by the member properties. In particular, post-peak behaviour and stiffness and strength degradation are often governed by local buckling of the compressed flange, and thus by the local slenderness of the cross-section [3].

Theoretically, the analysis of these phenomena could be performed via accurate three-dimensional Finite Element (FE) analysis, by using preliminarily calibrated constitutive relationships at material level, as investigated for instance in [4–7] for a wide range of different materials and geometrical configurations. However, for large-scale structural models, this kind of analysis may easily become prohibitive and thus simplified analysis based on one-dimensional beam elements is preferred. A good balance between computational demand and ease in the calibration is modelling the members as nonlinear Euler-Bernoulli beams in which the constitutive model at section level is evaluated by integrating the stress-strain relationship over the cross-section, i.e. the fibre approach [8]. However, this approach cannot take into account deterioration phenomena due to local buckling, unless more advanced concepts based on low-cycle fatigue are implemented in the material description [9]. A more common approach is that based on concentrated plasticity, in which all material nonlinearities in the beam are assumed as lumped in zero-length link elements at the beam ends. The constitutive relationship of the zero-length links may be formulated following two different strategies (Fig. 1): a) integrating the moment-curvature relationship over a predefined hinge length [10], or b) defining a specific moment-rotation behaviour accounting for softening and degradation (phenomenological approach). In both cases the interior part of the beam may be defined as elastic or nonlinear. Although approach (a) encompasses the possibility of incorporating axial-moment interaction and is characterised by a small number of material properties to define, to date it is implemented in a limited number of professional/research structural software packages. For this reason, the phenomenological approach is still widely used and will be considered in this work.

Specific hysteretic constitutive relationships for link elements should properly consider a number of nonlinear effects experimentally recorded in several applications, e.g. yielding, softening, degradation, pinching. Examples of advanced phenomenological models are those

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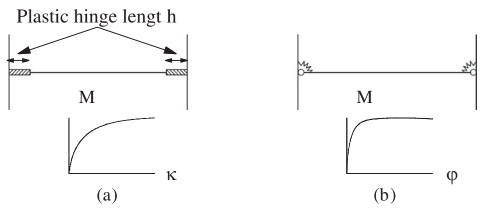

Fig. 1. Approaches to definition of plastic hinge behaviour.

developed by Takeda [11], Bouc and Wen [12,13], Ramberg and Osgood [14], Richard and Abbott [15], Dowell, Seible and Wilson [16], Sivaselvan and Reinhorn [17], Ibarra, Medina and Krawinkler [18]. The use of such models has the drawback that many material (or, better, model) parameters describing them cannot often be related directly to material and/or geometrical properties of the cross-section. Because of this issue, the calibration of phenomenological hysteretic models for zero-length links must be based on numerical fitting of experimental responses. A typical calibration procedure thus requires performing one ad-hoc experimental test, e.g. a bending test on a steel member according AISC protocol [19], and finding the numerical model (parameter set) which simulates the test response as accurately as possible. This turns out to be an optimisation problem, in which a scalar measure of the mismatch between experimental and computed responses is minimised.

When several outputs from tests on the same specimen are available, the optimisation problem becomes multi-objective because multiple possibly conflicting objectives, i.e. responses mismatches, must be minimised simultaneously. As detailed in the following sections, the solution of a such problem should be selected as a fair compromise between the different objectives. On one hand, this implies that the compromise solution is generally not optimal with respect to each individual response to fit; on the other hand, it is shown in previous research by the authors [20] that this approach may help solve the mathematical ill-posedness of the calibration problem. In fact, it was observed that a model fitting well the structural response of a beam under a cyclic increasing-amplitude static test may provide significantly inaccurate prediction of the behaviour of the same structural member when subjected to a strong-impulse ground motion. Conversely, if the monotonic response is added to the required responses to fit within the multi-objective optimisation approach, the prediction may improve in accuracy, especially in case of ground motions characterised by one or few impulses of very high intensity and all remaining impulses of significantly lower intensity.

In this work, a comparative study on the calibration of different hysteretic models for steel beams is performed. In particular, a simple hysteretic model (*Hyst*), the modified Ibarra-Medina-Krawinkler model (*IMK*), the Bouc-Wen model (*BW*) and the Sivaselvan-Reinhorn model (*SR*) are calibrated against the results coming from an experimental programme involving monotonic and cyclic testing of different types of steel sections. The motivation under this numerical study is threefold. The first objective of this work is comparing different models

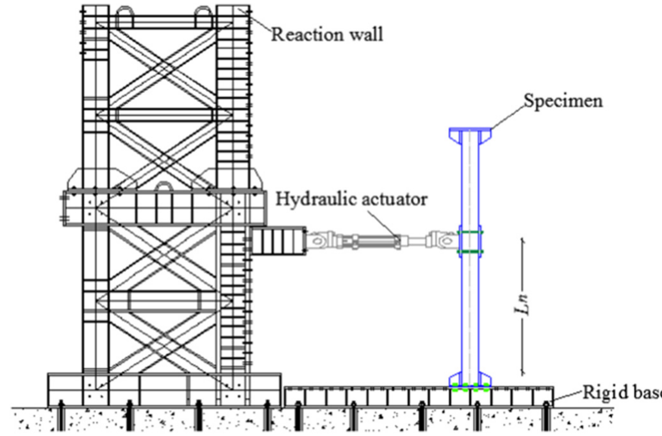

Fig. 2. Adopted set-up scheme for monotonic and cyclic tests.

on their ability to simulate both monotonic and cyclic behaviour of different typologies of steel beams. As a result of this extensive calibration exercise, the "best" model will be selected, as the one leading to the most accurate simulations for open and hollow cross-sections, under both monotonic and cyclic tests. Secondly, the multi-objective framework described in [20] is extended and improved in robustness by adding additional objectives related to the experimental tests. Finally, a relationship between the degradation parameters of the best model selected thus far and the local slenderness of the cross-section is proposed.

2. The experimental tests

A series of experimental tests, performed in the Laboratory of Materials and Structures of the Department of Civil Engineering of the University of Salerno, has been considered in this work. The general setup, the specimen description and the main outcomes are reported hereinafter; full details about the experimental programme may be found in [21]. The tests were carried out on three sets of steel sections:

1. Hot-rolled I and H cross-sections (HEA/HEB/IPE);
2. Cold-formed rectangular hollow cross-sections (RHS);
3. Cold-formed square hollow cross-sections (SHS).

For each set, three different sections were selected. Standard tensile coupon tests were performed for flanges and web. The mechanical and geometrical characteristics of the tested elements are listed in Table 1.

For each beam, one monotonic and one cyclic bending test were performed. The static scheme was that of a cantilever beam, of length $L_n = 1865$ mm (Fig. 2). An MTS 243.35 T hydraulic actuator with a maximum load capacity of 365 kN in compression and 240 kN in tension and a piston stroke equal to ±508 mm, fixed to a rigid braced steel

Table 1
Mechanical characteristics of the tested beams.

Set	Cross-section	f_y		f_u		I	W_{pl}	M_{max}	φ_{Mmax}	φ_u
		Flange [MPa]	Web [MPa]	Flange [MPa]	Web [MPa]	[cm^4]	[cm^3]	[kNm]	[rad]	[rad]
I and H cross-sections	HEA 160	337	338	460	475	1673	245.1	91.4	0.13	0.31
	HEB 240	284	354	441	421	11,260	1053	427.4	0.23	0.35
	IPE 300	316	349	439	454	8356	628.4	234.7	0.05	0.10
Rectangular hollow cross-sections	RHS 150 × 100 × 5	342	365	377	397	718.0	88.2	55.1	0.07	0.35
	RHS 160 × 80 × 4	315	333	346	376	597.0	92.8	38.2	0.03	0.21
	RHS 250 × 100 × 10	415	420	500	511	4384.0	462.0	274.5	0.11	0.18
Square hollow cross-sections	SHS 160 × 160 × 6.3	420	444	466	451	1438.0	212.0	98.9	0.03	0.34
	SHS 200 × 200 × 10	450	455	522	506	4228	507	288.8	0.07	0.32
	SHS 250 × 250 × 8	482	479	525	522	7214.0	675	372.9	0.03	0.21