Numerical Model Development for Cyclic Hardening Investigation of Steel-Yield Based Displacement Dependent Devices

V. Budaházy, A. Zsarnóczay, L.G. Vigh & L. Dunai
Budapest University of Technology and Economics (BME), Budapest

SUMMARY:
Design, testing and qualification of European Nonlinear Displacement Dependent Devices (NLD) are currently regulated by EN 15129, the European standard for anti-seismic devices. The objective of this study is to show that the hardening inherent in structural steel makes it difficult for steel-yield based displacement dependent devices to comply with EN 15129 requirements and propose an enhanced regulation for these devices. A material model has been developed, what accurately reproduces steel behaviour. A numerical model is built to test the behaviour of the developed material in a virtual experiment according to EN 15129 specifications. Although the model experienced the well-known stable hysteretic behaviour of structural steel, the variation of K2 stiffness is low, because the small initial reference value. This suggests that the current regulation does not address the stability of cyclic post-yielding hardening appropriately. A case study on buckling restrained braces (BRB) is made to show the effect of this regulation on the element level.

Keywords: Buckling restrained brace, displacement dependent devices, design procedure, cyclic steel material

1. INTRODUCTION

Anti-seismic devices are used to increase seismic resistance of structures by ensuring energy dissipation and nonlinear behaviour. The European general seismic design code Eurocode 8 Part 1 (EN 1998-1:2008) does not detail the design, testing and qualification of such devices; a separate specification EN 15129:2010, the European standard for anti-seismic devices addresses these issues.

When it comes to regulation of these innovative devices, the objective of various specifications in earthquake engineering standards is three-fold:
- ensure stable cyclic behaviour without significant cyclic degradation,
- prevent the excessive increase of axial load at the same displacement level in order to limit the overstrength applied at adjacent elastic members,
- provide an objective quality control measure for commercial products.

According to EN15129, overall behaviour of Nonlinear Displacement Dependent Devices (NLDs) can be characterised by the so-called Theoretical Bilinear Cycle (TBC) described as a bilinear force-displacement relationship similar to the backbone curve used in the United States (ANSI/AISC 341s1-05). Post-yield hardening rate of the TBC is controlled by the so-called second branch stiffness (K_2) measured in conjunction with two characteristic points in the plastic range (note that it is not related to the first-yield point). In order to ensure stable hysteretic behaviour, limitations on the variation of K_2 values measured in consecutive load cycles apply.

Plastic hardening of steel-yield based displacement dependent devices is typically characterised by larger hardening rate at small plastic deformation levels than at large ones. Additional problem the relatively small initial K_2 stiffness value caused by the small hardening rate at design displacement. Inelastic behaviour of these devices is influenced by their steel material, which is characterised by considerable cyclic hardening. In such case, the relative variation of the post-yield stiffness in the

consecutive cycles may be large, although its absolute value is acceptable with respect to stability of the cyclic behaviour. In behaviour of devices utilizing full yielding under axial loading the relatively small tangent stiffness is directly reflected. It is confirmed that the variation in stiffness and thus the performance of such devices is practically acceptable; moreover, typically superior to other devices owing stability behaviour. In design, due to the overstrength required for elastic members, the absolute ordinate of hardening is more important than the tangent stiffness variation. This observation queries the applicability of the current rules.

The final goal of this study is to show that the hardening inherent in structural steel makes it difficult for steel-yield based displacement dependent devices to comply with EN 15129 requirements and propose an enhanced regulation for these devices: an alternative approach capable of limiting the variation of post-yield hardening without being sensitive to the shape of the nonlinear force-displacement curve.

In the current phase of the research, a numerical model has been developed for cyclic material behaviour modelling and for application in modelling of seismic devices. Real and virtual experiments are being completed on common steel material samples as well as on simple and complex seismic devices, such as buckling restrained braces (BRB). The results well confirm that the current regulation does not address the stability of cyclic post-yield hardening appropriately; and support the development of new proposal for alternative criteria.

This paper focuses on the numerical model development for cyclic material model behaviour. Model development and calibration is discussed in details. Problematic points of the current regulation and alternative approaches are illustrated on the material level, using virtual experimenting method. A case study on BRB is made to show the effect of this regulation on the element level.

2. THE HARDENING VARIABLE AND QUALITY CONTROL OF NLDS

As per EN15129, behaviour of NLDs is described by the Theoretical Bilinear Cycle (TBC) curve represented by the so-called first and second branch stiffnesses, K_1 and K_2, respectively (Fig. 2.1/a). K_1 is the initial – elastic – stiffness; K_2 is a secant stiffness measured between two points on the experimental force-displacement curve:

$$K_2 = \left[V_{EBd} - V(0.5 \cdot d_{bd}) \right] / (0.5 d_{bd}) \tag{2.1.}$$

where $V(x)$ is the force value corresponding to displacement x; d_{bd} is the so-called design displacement that is the total displacement the device is subjected to in case of the design seismic action specified in EC8-1. The limiting criterion of EN 15129 is as follows:

$$\kappa = \left| K_{2,i} - K_{2,3} \right| / K_{2,3} \le 0{,}10 \qquad i > 1 \tag{2.2.}$$

where $K_{2,i}$ is the second branch stiffness at i^{th} load cycle. The allowable cyclic degradation or increase depends on the K_2 stiffness of devices. However, due to K_2 depends on the design displacement; it is not only influenced by the particular type of device but also by the loading conditions. The presented formula makes it possible to result different K_2 value, and different variation limit on the same device. Steel material is another important factor. Typical stress-strain curves from cyclic loading of regular steel demonstrate that the material stiffness significantly decreases with increasing plastic strains (Fig. 2.1/b.), (Beer, Johnston, Dewolf and Mazurek, 2009); i.e. the tangent of the stress-strain curve at the plastic region – denoted as $K(d_y)$ – is typically reduced to 20% of the elastic stiffness K_1 after the yielding point is reached, moreover further reduction is experienced at larger deformation (refer to $K(d_{bd})$) where it is less than 5 % of the initial slope. The same behaviour is experienced in steel-based NLDs under axial loading (Zsarnóczay and Dunai, 2011). This small tangent results small K_2 value, and limits the acceptable variance in forces measured.

As a further conclusion of the above observation, depending on the design displacement, same type NLDs have different characteristic TBC curves, however difference of hysteresis loops may be less than 1% of the load capacity causing by the small vale of K_2. The authors believe that the resulted treatment is unnecessarily strict, which might hinder their use.

Based on US specifications and approaches, an alternative quality control of NLD devices is proposed in (CE 2011). Post-yield behaviour of NLDs can be described with the backbone curve. The two important parameters of the curve are called tension (ω) and compression (β) strength adjustment factors (Fig. 2.1/c.):

$$\omega = V_{bd,T} / R_{y,a} \quad \text{and} \quad \beta = V_{bd,C} / V_{bd,T} \qquad (3.1.)$$

where $V_{bd,T}$ and $V_{bd,C}$ correspond to the design displacement under tension and compression; $R_{y,a}$ is the actual cross-section resistance (the product of the actual yield stress of the steel material and the core cross-section). The ω factor is the tangential stiffness of the device between the yielding point and the design displacement, under tension, while β describes the difference between the tension and compression post-yield hardening rate. The authors believe that a quality control requirement shall only be depend on the characteristics of the device. Therefore, instead of design displacement level, a device specific reference strain level (ε_{ref}) is used for the determination of the device representative ω and β values. (Note that for design purposes the design displacement is to be used.) This strain level shall be the maximum the given device can reliably work. Variance of post-yield behaviour shall be constrained by limiting the variance of ω and β. The authors recommend an acceptable variance in ±15% which is in line with the limits for other properties specified in EN 15129.
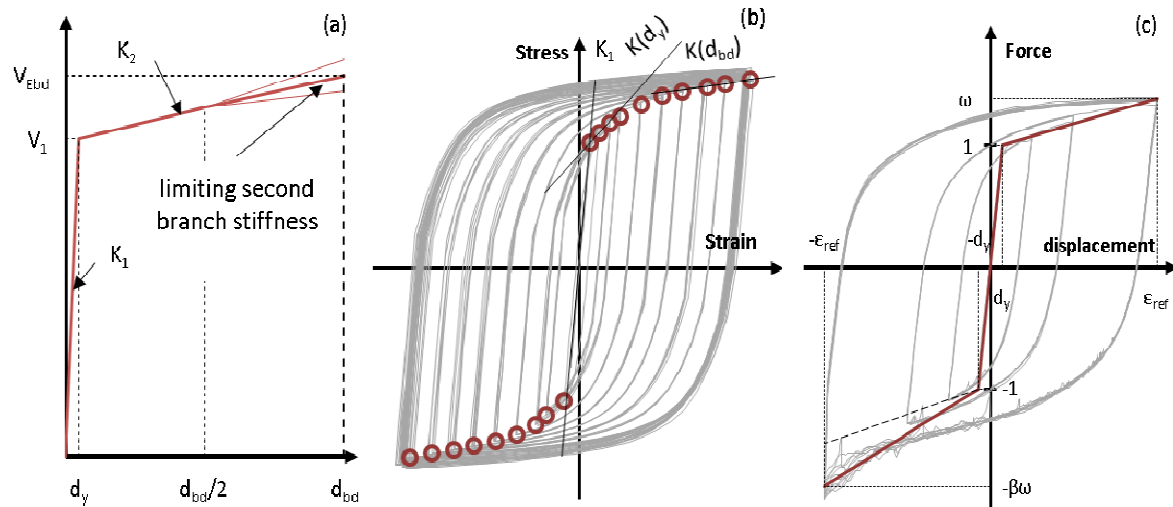

Figure 2.1. (a) Characteristic of TBC curve; (b) Typical force-displacement response of steel under proportional cyclic loading (c) Alternative strength adjustment factors, fitted on numerical NLD device result

The alternative control method for NLDs has several advantages over the current regulations:
- It excludes the discussed cyclic stability control problems and better represents the overall variance in seismic performance.
- It uses normalised values, thus the performance of different devices is directly comparable.
- The described parameters depend on the whole range of post-yielding behaviour, while the K_2 stiffness not, often failing to approximate the force-displacement curves under small plastic deformation.
- It can distinguish the difference between tension and compression behaviour with β value.

3. MODEL DEVELOPMENT AND CRITERIA VARIATION ON MATERIAL LEVEL

The two presented quality control method of NLDs are compared both on material and device levels. Following the EN 15129 specifications, standard load protocol was used. The numerical models were developed in ANSYS final elementary program (ANSYS, 2007).

3.1. Experimental laboratory test results

The numerical material model is calibrated and verified using partly an independent cyclic test results from literature (Youngjiu, Meng and Yuanqing, 2011) and partly own monotonic test result (Zsarnóczay and Dunai, 2011). Youngjiu et. al. describes the result of large number of different cyclic loading scenarios on a specific steel material (Q345B) common in China. The experimental monotonic and hysteresis behaviour, ductility characteristics and cumulative damage degradation are discussed in the paper in detail. The yield stress and the ultimate stress was $f_{y,Q345}$=429 N/mm^2 $f_{u,Q345}$=589 N/mm^2.

Yielding point and strain hardening rate of this material model are adjusted to account for the - difference in yield stress and ultimate stress of the common European steel grade S235, often applied in NLDs. In case of the BRB discussed in Section 4, the actual properties are $f_{y,BRB}$=290 N/mm^2 and $f_{u,BRB}$=426 N/mm^2. The numerical model is first calibrated to the curves of Q345B, secondly, the parameters are rescaled to get appropriate yield and ultimate stress. This scaling does not affect post-yield cyclic hardening behaviour.

3.2. Mild steel material model development

In order to analyse the two quality control method, a material model that is capable to describe all the important material factors and phenomena has to be developed. These factors are: kinematic hardening, saturation of Bauschinger effect, decrease of the yielding surface, disappearance of the yielding plateau, plastic creep, and strain memory, (Budaházy and Dunai, 2011). Different accuracy of steel material models have been investigated and developed in ANSYS program (Budaházy and Dunai, 2012).

The following proposed numerical model is not only able to describe the above effects, but also effective for numerical calculations. A dynamically updated material model (named by the authors as *PRESCOM* – Parameter Refreshed and Strain Controlled combined Chaboche (Chaboche, 2008) model with isotropic hardening) consists of five superposed Chaboche models combined with a multi-linear isotropic hardening.

3.2.1. Fem model for analyse material behaviour

The behaviour of material models are examined using a simple finite element model of a rectangular element (denoted as SOLID 185 in ANSYS) (Fig. 3.1.). The boundary condition is defined considering Poisson effect, and the analyse type is quasi-static, displacement controlled. This model represents the pure material behaviour, without any influence of structural system it is used in.
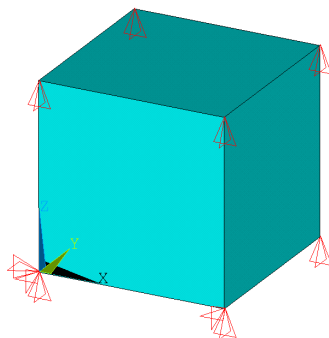

Figure 3.1. FEM model used for material development

3.2.2. General parts of PRESCOM model

Steel material behaviour is very different under monotonic and cyclic loading conditions (Beer et. al., 2009). The yielding plateau gradually disappears, and the normalised size of yielding surface decreases proportionally to the accumulated plastic strain. This behaviour is simulated in PRESCOM model by three parameter sets. The first (*monotonic set*) describes the monotonic steel behaviour, the second corresponds to cyclic steel behaviour (*cyclic set*). In order to reproduce the change between pure monotonic and cyclic material behaviour a further, third state is defined (*transitional set*). In this state a function is used to calculate model parameters continuously updating. Two state variables are examined considering experimental results: (i) the maximum value of plastic strain (ε_{EQW}), and (ii) the maximum value of strain range (the difference between maximum and minimum strain levels in a unidirectional load path; dp_{MAX}). Although saturation of the Bauschinger effect and the decrease of the yield surface depend on the maximum plastic strain, the stress-strain relationship at the small strain range is also influenced by the previously experienced maximum strain range (Lee and Chang, 2000). The optimal approximation is obtained when the maximum of ε_{EQW} and dp_{MAX} is used as state variable in the model (Eqn. 3.1.):

$$\varepsilon_{RPL} = \max(\varepsilon_{EQW}, dp_{MAX}) \qquad \text{where } \varepsilon_{RPL} \text{ is called the relevant plastic strain} \qquad (3.1.)$$

3.2.3. Dynamic parameter calculation method

The algorithm of the dynamic model parameter calculation is illustrated in Fig. 3.2. At the beginning of the loading path the monotonic parameter set is used for every steel element in the dissipative zones of the structure. After the first load step, the maximum value of equivalent plastic strain is evaluated, and the material model constants are updated using the following logic: if the value of the plastic strain is zero, the parameter set is kept monotonic. If it is greater than a pre-defined limit (ε_{EQW2}), the cyclic parameter set is adjusted to the model. If the plastic strain falls within the range $0 \sim \varepsilon_{EQW2}$, the behaviour can be described by the transitional parameters, using the function of relevant plastic strain. The maximal equivalent plastic strain and the maximum strain range are evaluated after each load step. If the new relevant strain is greater than the previous one, the parameter set of the model is updated using the above procedure. If the relevant strain did not change, the parameters also keep. This procedure builds the hardening memory effect at the critical range of small plastic strains into the material model using the relevant plastic strain to describe the change in material behaviour.
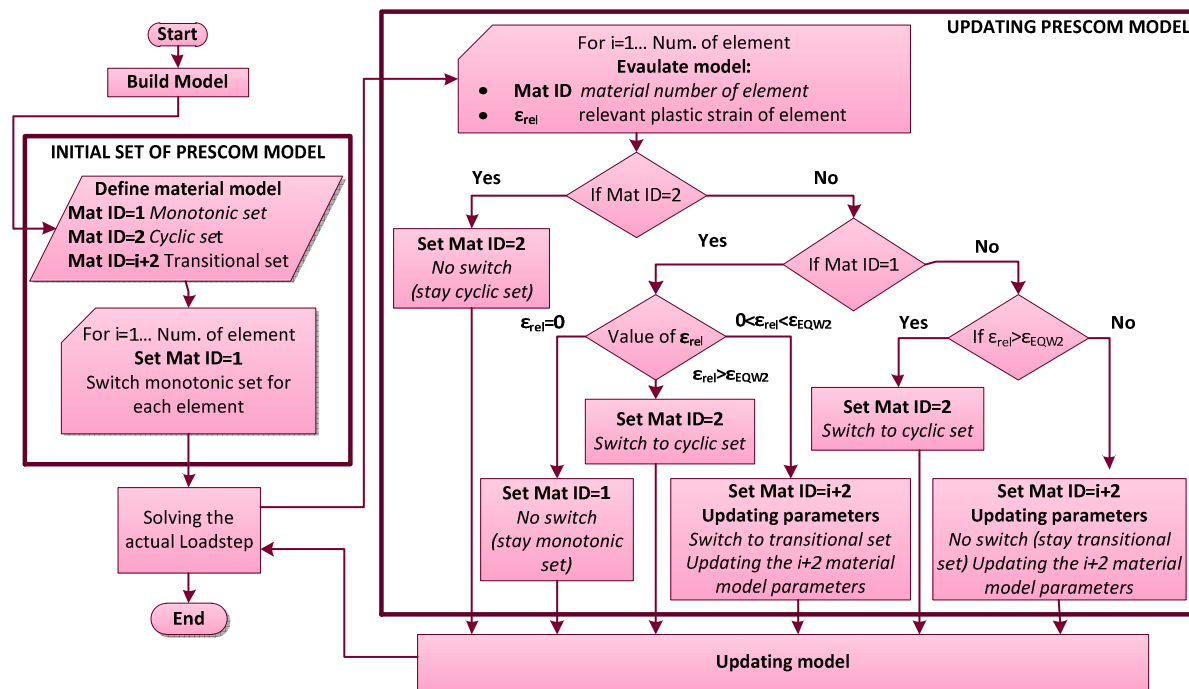

Figure 3.2. Parameter updating of PRESCOM model

Except for the monotonic stage where the yielding point corresponds to the virgin state, the numerical model applies the so-called saturated yield stress ($f_{y,num}$) that refers to the decreased yield surface. The yield surface gradually decreases after each consecutive load cycle depending on the maximal strain level reached during the given cycle. In spite of this yield surface reduction, the stress at the maximum strain level cannot decrease during cyclic loading. Therefore, the hardening rate of the model has to be increased parallel with the shrinkage of the yield surface. At the transitional range the model parameters are updated to reach the appropriate stress level when the strain amplitudes reach the maximum. The material model contains five simple Chaboche models (Table 3.1). The first Chaboche model reproduces the hardening between the virgin and the saturation tendencies (Eqn. 3.2.), while the second and third models describe the hardening observed in cyclic experiments (Eqn. 3.3.).

$$\frac{\Delta\sigma_i}{2} = \frac{C_i}{\gamma_i}\tanh\left(\gamma_i\frac{\Delta\varepsilon_p}{2}\right) \quad \text{where } \gamma_i\frac{\Delta\varepsilon_p}{2} = 2.5 \tag{3.2.}$$

$$C_i = \left(\frac{\varepsilon_{RPL}}{\varepsilon_{EQW2}}\right)^{\alpha} C^0_i \quad \text{where } i = 2 \text{ or } 3 \text{ and } \alpha = 1.5 \tag{3.3.}$$

Table 3.1. Parameters of PRESCOM model

$f_{y,num}$=202 MPa	Cyclic material model					Transitional model		
$f_{y,real}$=290 MPa	Chaboche models			Multi-linear		Chaboche models		
Chaboche model no.	C	γ	$\Delta\sigma$	ε_{pl} [-]	σ	C	γ	$\Delta\sigma$
I.	25000	500	50	0	195	f(ε_{EQW}, $\Delta\sigma$, β)		$\Delta\sigma$
II.	21000	375	56	0.05	260	f(ε_{EQW2}, α, C_{02})		
III.	5950	120	49,6	0.1	217	f(ε_{EQW2}, α, C_{03})		
IV.	935	25	37,4	4.5	267	935	25	37,4
V.	300	0				f(ε_{EQW})	0	

Approaching the transition end, the PRESCOM model shall tend to the model with the cyclic parameter set. The stress level at a given strain rate depends on the load history, resulting in different stress values at the same strain level. This phenomenon is taken into consideration at transition model, with increasing coefficients at second and third models, and decreasing at the fifth Chaboche model. The details of parameter updating is in (Budaházy and Dunai, 2012).

3.2.4. Monotonic and cyclic behaviour
The presented results are rescaled for the measured strength parameters of S235. The calibrated results for Q345B is detailed in (Budaházy and Dunai, 2012), and compared to experimental results. As the result of the above detailed procedure, the PRESCOM model is able to describe the observed performance. Fig. 3.3 and 3.4 illustrates the model behaviour under static and cyclic loading, respectively. The obtained results are sufficiently accurate.
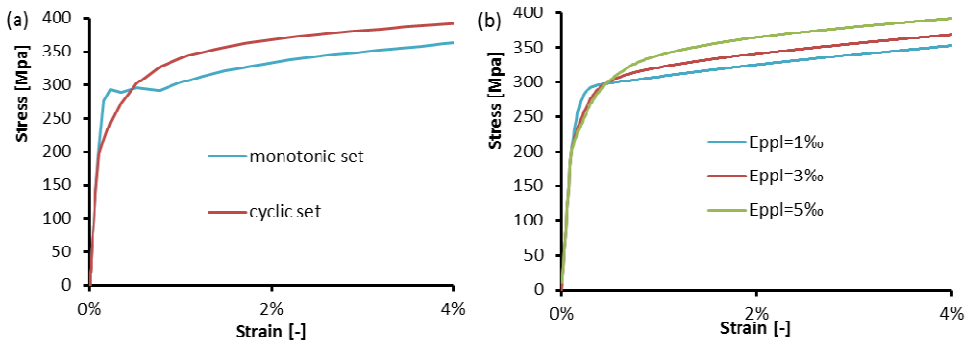

Figure 3.3. Behaviour of PRESCOM model under monotonic loading: a) pure virgin and cyclic behaviour; (b) in the function of maximal relevant plastic strain experienced in preloading
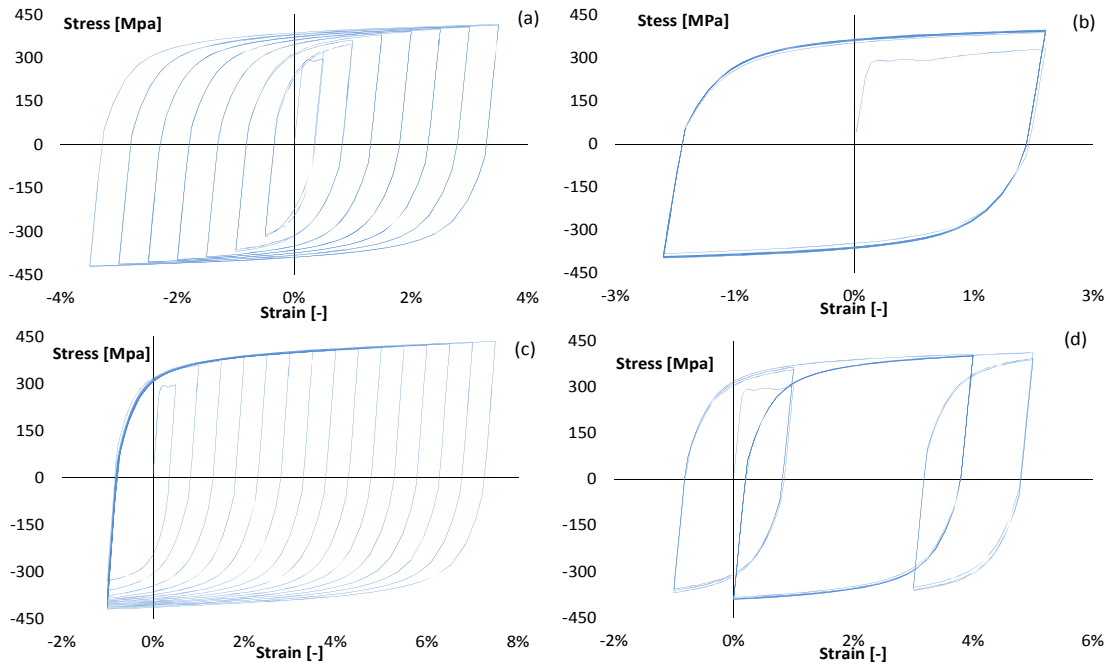
Figure 3.4. Behaviour of the developed model under cyclic loading with (a) proportionally increased amplitudes of loading; (b) constant proportional loading; (c) non-proportionally increased amplitudes of loading; (d) non-proportionally increased loading with various amplitudes

3.3. Evaluation of cyclic hardening variation and quality control method

The above described FEM model is able to describe the pure material behaviour without any confounding factor. The accuracy of the model has been proven by different loading conditions. The force-displacement curve of material is shown on Fig. 3.5. (The stress-strain curve was converted following the EN 15129 specifications, because the investigated parameters correspond to force-displacement curves.) Evaluation of the cyclic hardening results confirms that the pure steel cyclic behaviour cannot satisfy the current EN 15129 regulations (refer to Fig.3.5b, region enclosed by purple dashed lines). On the contrary, the strength adjustment factors stay within the prescribed limits of the alternative regulation proposed in Section 2 (refer to the region indicated by the blue dashed lines). For further details refer to (CE, 2011).
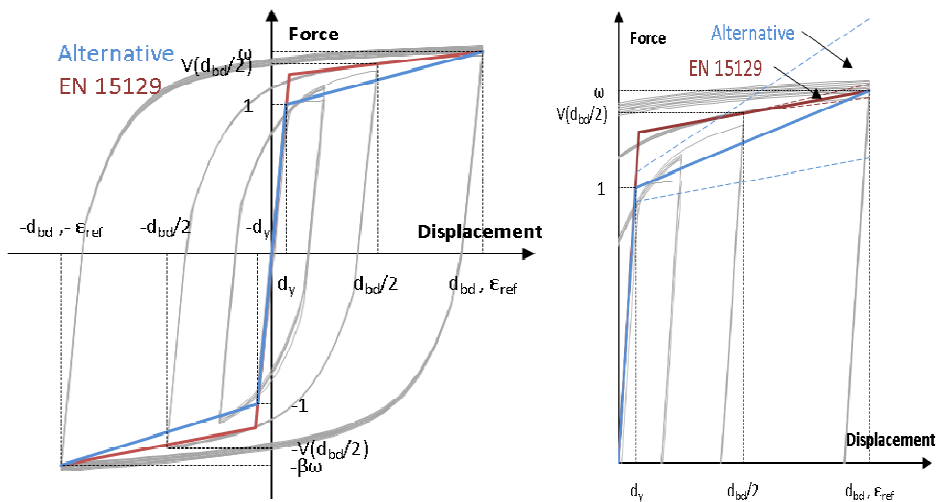

Figure 3.5. Force-displacement curve from numerical steel material whit two types of bilinear relationship, and the acceptable variation of post-yield stiffnesses
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4. MODEL DEVELOPMENT AND CRITERIA VARIATION ON ELEMENT LEVEL

After the material level analysis, a Buckling Restrained Braces (BRB) is analysed using the developed material model and alternative cyclic hardening criteria evaluations are illustrated. Buckling Restrained Braced Frame (BRBF) is typical anti-seismic solution in the USA and Japan. The advantageous dissipative properties of the steel material are taken with these devices to the structural level; by limiting the amplitude of buckling of pressured bracing element, and resulting in frames capable of significant energy dissipation. The BRB has three components: a slender steel core, where the energy can be dissipated; a concrete casing in a steel hollow section, which supports the core laterally under compression; and an air gap separating the former two parts from each other.

4.1. Experimental laboratory test of BRB

Displacement controlled quasi-uniaxial cyclic load tests have been performed at the Structural Laboratory, Budapest University of Technology and Economics, on a total of six specimens using a combined loading protocol of EN 15129 and (ECCS, 1986) for model calibration. For details on each test refer to the test reports (Zsarnóczay and Dunai, 2011).

4.2. Description of the numerical model

In the numerical model, solid element are applied. The complexity of the BRB devices requires the use of several advanced modelling tools, such as combined hardening, cyclic material plasticity, plastic buckling, contact problem and friction. The four major parts of the model are shown in Fig. 4.1. The scaled PRESCOM model is adjusted with the core, while the casing and the concrete are elastic.
Serendipity element type and quadratic mesh is used, resulting in the most accurate solution of a given element size. In order to reduce computation time and improve convergence, symmetry plains are defined and one quarter of the member is modelled (Fig. 4.2). Analysis type is quasi-static displacement controlled according to experimental test and standards specifications, whit automatic time-stepping. The maximum numbers of iteration was maximized in 200 on a sub step. In order to improve convergence, special contact parameters were used, and the normal penalty stiffness factor (FKN) and the penetration tolerance factor (FTOLN) were set to get more soft contact. (FKN was set form 1 to 0.1 and FTOLN was set from 0.1 to 0.01).
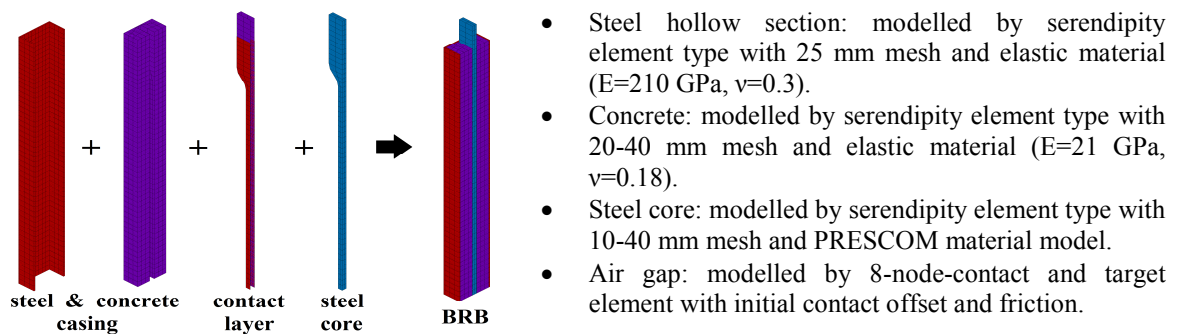

- Steel hollow section: modelled by serendipity element type with 25 mm mesh and elastic material (E=210 GPa, ν=0.3).
- Concrete: modelled by serendipity element type with 20-40 mm mesh and elastic material (E=21 GPa, ν=0.18).
- Steel core: modelled by serendipity element type with 10-40 mm mesh and PRESCOM material model.
- Air gap: modelled by 8-node-contact and target element with initial contact offset and friction.

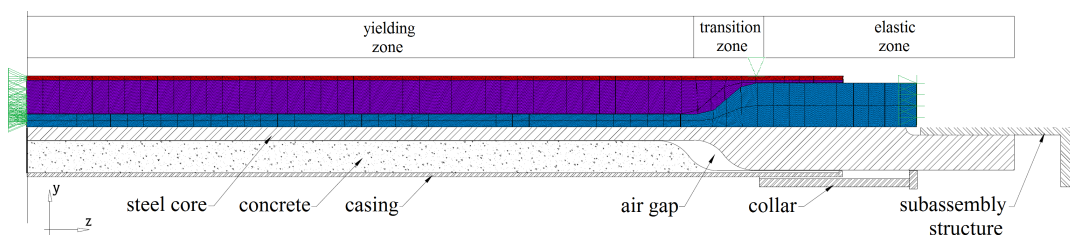**Figure 4.1.** Features of numerical BRB model

Figure 4.2. Typical longitudinal section, mesh and boundary condition of model

The numerical model was calibrated by test results, they are in good agreement and the accuracy of the model is satisfactory as confirmed by Fig. 4.3/a. The model is able to describe all the important behaviour factors including the pinching effect as well. Fig. 4.3/b. shows the updating of PRESCOM model during the loading. After the 1th load cycle, the brace stayed elastic and monotonic set is used. The first plasticity of core appears after the 5th load cycle, at transition zone (see Fig. 4.2). As the deformation amplitude is increasing, the plasticity extends to the whole yielding zone at 10th cycle, switching the PRESCOM model to transitional state. With increasing relevant plastic strains, the number of cyclic set element is growing. After the 30th load cycle, the whole yielding zone is switched to cyclic set.
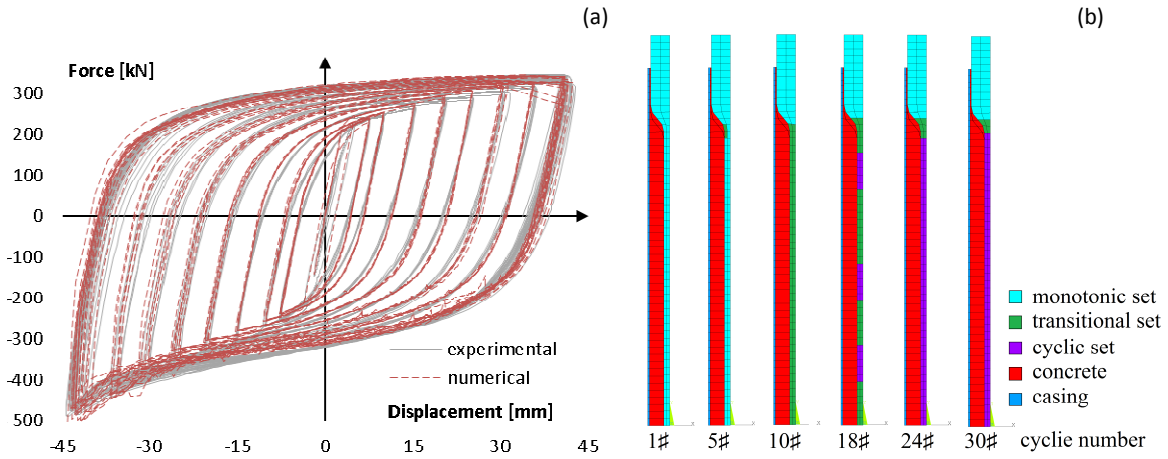

Figure 5.3. (a) Verified BRB model, and test results; (b) updating of PRESCOM model

4.3. Evaluation of cyclic hardening variation and quality control method at element level

The behaviour of an NLD device can be simulated with the calibrated model. According to EN 15129 specifications, the same virtual standard experiment has been performed on element level as material. The results of the analysis and the cyclic hardening criteria evaluation are summarized in Fig. 4.4. Under tension the curve of element hardly differ from the one of material level, and the same conclusions can be drawn. At compression, where friction may considerably modify the centrally-symmetric curve of steel material, the slope of TBC curve becomes larger, and the variance covers greater range.
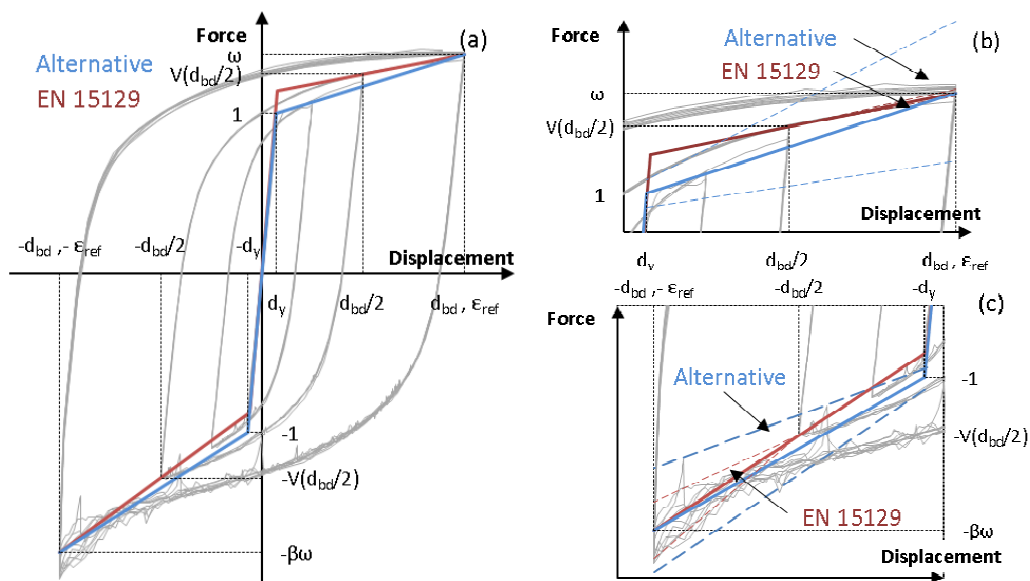

Figure 4.4. (a) Force-displacement curve from numerical steel material whit two type of bilinear relationship, and the acceptable variation of post-yield stiffness (b) at tension (c) at compression.

In spite of the increased rate of cyclic hardening, the strength adjustment factors well describe the overall element behaviour and provides solid base for cyclic hardening criteria evaluation and control of cyclic performance, (CE, 2012).

CONCLUSION

A special Chaboche-based cyclic mild-steel material model is developed and calibrated for cyclic hardening investigation for displacement dependent devices. Detailed description of the dynamically parameter updating method is given and the proper performance of the model is confirmed at different loading conditions. Based on the developed material model a BRB model is also developed and calibrated by experiments. Using these models a comprehensive analysis has been performed on an alternative quality control method focusing the post-yielding behaviour of NLDs. The alternative approach is evaluated and compared to EN 15129 specifications. The suggested, more general, comprehensive cyclic hardening variation and quality control method better describes the device behaviour and it is more objective.

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