Prediction of available rotation capacity and ductility of wide-flange beams: Part 1: DUCTROT-M computer program

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1. Introduction

Today’s challenge, for a proper seismic design, is to solve the balance between seismic demand and structural capacity. Seismic demand corresponds to the earthquake effect on the structure and depends on the ground motion characteristics. Structural capacity is the ability of the structure to resist these effects without failure. Looking to the development on topics of Engineering Seismology and Earthquake Engineering, it is very clear that the major efforts of researchers were directed toward the structural response analysis. Therefore, the structural response can be predicted fairly confidently, but these achievements remain without real effects if the accurate determination of the seismic actions is doubtful. In fact, the prediction of ground motions is still far from a satisfactory level, due to the complexity of the seismic phenomena [2,4].

Hence, in the design of earthquake-resistant structures, the structural designer is confronted with many uncertainties. The checks, which are required to assure a suitable behavior of a structure during a seismic attack, must be examined in the light of three levels of design approach namely; serviceability, damageability and ultimate limit states. For the first two limit states the exceeding of design values as compared with seismic actions cannot produces important effects. In exchange, in case of severe earthquakes when the structure attains the ultimate limit state or the near collapse behavior, the great uncertainty due to the variability, dispersion and scatter, in the evaluation of seismic design forces seems to be the rule and not the exception. The result can be the total or partial structure collapse, which is not accepted by the Seismic Design Philosophy.

In order to consider this situation, the structure must be endowed by design with corresponding ability to develop and maintain its bearing capacity, even when the considered seismic action exceeds the design limits. A measure of this ability, named robustness, is the ductility, which is the structural performance to sustain these exceeding by large deformations in plastic range without significant loss of resistance. The ductility could be defined as a function of loading type acting on the structure (monotonic or cyclic ductility). The capacity to predict the available ductility particularly under seismic loads is a key-point in structural design. A measure of the ductility is the plastic rotation capacity of a section. Unfortunately, in present design specifications, there are no provisions concerning the determination of this rotation capacity. Furthermore, the difference between monotonic and cyclic ductility is not recognized. The Eurocode 3 (EN 1993–1:2005) [5] proposes the classification of structural cross-section into four ductility classes: ductile, compact, semi-compact and slender. The same classification is also specified to the Eurocode 8. Evidently only the first three classes can be considered for seismic design. The main critics of this classification refer to the sole use of cross-section characteristics to determine the ductility. Therefore, the 2005 Italian code [6] introduces classification criterion into three ductility classes, ductile, plastic and slender, using
the characteristics of steel members and based on the over-strength factor.

In the frame of performance-based design a structure, under a specific ground motion, is sized in order to behave within code prescribed bounds. To achieve these levels of verification, the seismic design is laid out through required available formulation [2]:

\[
\text{REQUIRED CAPACITY} < \text{AVAILABLE CAPACITY}
\]

Currently, the required-available pairs of three mechanical characteristics are considered in earthquake resistant design, namely rigidity, strength and ductility:

\[
\text{REQUIRED RIGIDITY} < \text{AVAILABLE RIGIDITY} \\
\text{REQUIRED STRENGTH} < \text{AVAILABLE STRENGTH} \\
\text{REQUIRED DUCTILITY} < \text{AVAILABLE DUCTILITY}
\]

In a coherent earthquake design strategy, the structure must be verified for rigidity at serviceability level, for strength at the damageability level and for ductility at ultimate limit state.

According to these verifications, one can remark that, in the first two ones there are no difficulties to perform these verifications, but for the last one, referring to ductility, the verification is far to be satisfactory. The main reason is the difficulty to define the required and available ductility which are based on the very vague codes provisions [2]. In addition, the new design philosophy considers that the required ductility must by defined in function of earthquake characteristics [4]:

(i) Reduced ductility but high strength (reduced \( q \) factor) for earthquakes with short duration and reduced number of cycles.
(ii) Moderate ductility and moderate strength (medium \( q \) factor) for earthquakes with moderate duration and number of cycles;
(iii) High ductility but reduced strength (high \( q \) factor) for earthquakes with long duration and large number of cycles.

where \( q \) is the behavior factor.

This classification, characterized by the reduced or large number of cycles, is given in function of the structural capacity to dissipate seismic energy. In this way, a comprehensive methodology is required that takes into account the possibility to calculate the structural ductility (reduced, moderate or high) depending on earthquake characteristics. The aforementioned target is not allowed by the existing code rules until now.

A solution to improve this situation is to define the ductility using the rotation capacity of structural members. Therefore, analytical or numerical methodologies for determining the available rotation capacity of steel members are of crucial importance for seismic design. Among the existing methodologies (experimental, theoretical and empirical), it was proved that the most efficient for design purposes is the local plastic mechanism model based on yield lines and plastic zones [1,2].

2. Investigations in local plastic mechanism models

During the experimental tests on the steel wide-flange beams one can observe that the plastic deformations are produced only in a limited zone. The rest part of the beam remains in elastic field. In this plastic zone large rotations are concentrated, working as plastic hinges. The inelastic rotations are amplified if in these zones plastic buckling of flange and web occurs. Two main buckling types were distinguished during the experimental tests, the in-plane and out-of-plane buckling modes [7] (Fig. 1).

After these first experimental results, a series of tests, presented in [1,2], were performed, confirming the obtained results. Two types of beam specimens were used, with one or two transversal forces, also having different moment variations in zones were plastic hinges are considered to be formed. The first loading system models the moment gradient while the second one, the constant moment. Important differences between the obtained results are observed, indicating that moment variation is an important factor in determining the beam ductility.

Following this experimental results, a series of studies involved in analytical expression of moment–rotation curves in plastic range, were performed. The first application of the plastic mechanism method can be considered the paper of Climenhaga and Johnson [8], which considers the plastic hinge formed by flange and web. The proposed model is in good correspondence with experimental tests. The most important aspect of this paper is the fact that the both in-plane and out-of-plane are considered. An important progress in application of this methodology was performed by Ivanji [9], based on the principle of the virtual work in order to analyze the local plastic mechanism. Kuhlmann [10] and Feldmann [11] proposed a plastic mechanism for in-plane plastic buckling, in which the interaction of flange and web is considered.

An intensive research work was started in Timisoara from 1989 to determine the ductility of wide-flange members using the local plastic

![Fig. 1. Plastic buckling types for standard beam SB 1 [1]: (a) In-plane buckling; (b) Out-of-plane buckling.](image-url)
mechanism methodology, for both in-plane and out-of-plane plastic buckling modes. The first results, including the development of computer programs POSTEL and DUCTROT 93, were published in [12,13]. The research was continued and further results were published [1], while a new improved version of computer program, the DUCTROT-96, was elaborated. The proposed methodology allows determining the rotation capacity and ductility in function of all geometrical and mechanical parameters.

The main conclusion of these studies is that the plastic buckling operates as a filter against large strains in tension flange, reducing the danger of cracking. A synthesis of these research works and some applications of this methodology were published in [14–16].

Another step in research works performed at Timisoara University was devoted to modify the collapse mechanism, mainly for improving the dimensions of plastic zone of flange local mechanism and the shape of web local mechanism. On the basis of these optimized local plastic mechanisms, an evolution of the abovementioned software was made with the elaboration in 2002 of DUCTROT-M computer program [17]. With the aid of this one new series of studies were performed and the results were published in [2,18]. A very good correspondence between numerical results and experimental tests was obtained further validating the accuracy of the DUCTROT-M. Details concerning the new shape of plastic mechanisms for in-plane and out-of-plane mechanisms can be found in [2]. Additionally, more in depth investigations regarding the evaluation of the rotation capacity of steel members were published in [19–21].

In the last period, based on the development presented in [8], local plastic mechanisms were proposed to study the behavior of steel members under low-cycle fatigue [22,23], or fire conditions [24].

3. DUCTROT-M computer program

3.1. Modeling the member behavior

The available rotation capacity must be determined taking into account that the member belongs to a structure with a complex behavior. But this is a very difficult task, due to the great number of factors influencing the behavior of the actual member. Thus, it is important to simplify the analysis by using for the actual member a simple substitute element with a very similar behavior. This member is so named standard beam, used for the first time in [1] to determine the rotation capacity.

Fig. 2a shows the behavior of a framed structure, where the inflection points divide the beams into two portions, with positive and negative bending moments. The rotation capacity of the beam ends must be determined in different conditions. For positive moments, the plastic hinge works in a zone with quasi-constant gradient, while for negative moments, under important moment gradient (Fig. 2b). Therefore, the actual behavior of a member in a structure can be replaced with the similar behavior of two standard beam types: the SB 1, with a central concentrated load for the zone under quasi-linear moment gradient, and the SB2, with a distributed load for the zone with weak moment gradient (Fig. 2c). Considering that the inflection point is situated at (0.2–0.3) Lb, the relation between standard beam span, L, and real beam in a structure, Lb, is:

<table>
<thead>
<tr>
<th>Standard beam span, mm</th>
<th>Beam span, mm</th>
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<tbody>
<tr>
<td>2000</td>
<td>3500...5000</td>
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<tr>
<td>3000</td>
<td>5000...7500</td>
</tr>
<tr>
<td>4000</td>
<td>6500...10,000</td>
</tr>
<tr>
<td>5000</td>
<td>8000...12,500</td>
</tr>
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3.2. Computer performances

However, the present paper is focused only to the phenomenological aspects of the utilized collapse mechanisms which are considered as a basis for the development of the aforementioned software. The characteristics of DUCTROT-M computer program are published in [2,18], where mainly all mathematical aspects are discussed.
The algorithm is presented in Fig. 3. The computer program determines the following characteristics for wide flange members:

(i) General characteristics:
- material characteristics considering the random variability of superior limits for yield stress;
- cross-section characteristics with the limits to prevent elastic buckling and brittle fracture;
- member characteristics considering loading systems (SB1 and SB2 standard beams), member span and axial force.

(ii) Ductility characteristics for monotonic loads:
- two main curves of plastic buckling which determines in-plane and out-of-plane plastic mechanisms;
- moment–rotation curves for the two mechanism types and for gradient or quasi-constant moments;
- determination of ultimate rotation and rotation capacity for the defined level related to fully plastic moment (1.0 or 0.9);
- main geometrical dimensions of plastic mechanism shape;
- influence of the beam–column connection details;
- selection between in-plane and out-of-plane plastic mechanism;

![Fig. 4. Evolution of local plastic mechanism shapes [2].](image)
– influence of fabrication type: rolled or welded (filet or penetrated welds).

(iii) Ductility for seismic loads:
– influence of pulse loading, in function of strain-rate level and exterior temperature;
– influence of cyclic loading, in function of cycle type (increasing, constant or decreasing) and cycles number.

The present paper deals with the ductility defined under monotonic loads. The principle that the results from monotonic actions can be also used for seismic actions is accepted in the Eurocode 8 (earthquake resistant design) by applying the same ductility classes prescribed in Eurocode 3 (static design). In any case for exceptional seismic actions with specific features, as pulse or multi-cycle characteristics, the monotonic values must be corrected. The abovementioned topic constitutes an open issue currently under investigation. However, details for seismic effects on the available ductility can be found in [2].

The computer program DUCTROT-M is now free available on CD-ROM as an appendix of the book [2] or free on the site [3].

4. Local plastic mechanisms for gradient moment

4.1. In-plane local plastic mechanism

This local plastic mechanism is characterized by deformation situated in the beam plan, without lateral displacements of flanges (Fig. 1a). The shape of collapse mechanisms observed during the experimental tests is composed by yield lines (true mechanism) or by combination of yield lines and plastic zones (quasi-mechanism). The last mechanism type involves a large amount of energy than the first type, due to the membrane yielding of plastic zone [2].

A progress in function of the attempt to transform the experimental mechanism into analytical and numerical models can be noted (Fig. 4).

The Climenhaga and Johnson [8] as well as Ivanyi's [9] collapse model is based on a perfect symmetry in relation with vertical axis, and considers the length of flange and web plastic zone equal with the flange width. The POSTEL [10] and DUCTROT 93 [13] computer programs are based on these considerations.

Kuhlmann's model [10] is based only on yield lines, for symmetric local plastic mechanisms, formed by plastic buckling of compressed flange and compressed part of web. Feldmann's model [11] considers only the collapse mechanism formed in compressed flange.

The version of DUCTROT-96 computer program was based on an improved mechanism, implementing a more suitable shape for the local plastic deformations of flange and web. However, examining more careful the experimental tests [25] one can observe that the opposite is true, namely the width of web plastic zone is different in comparison with the flange one (Fig. 5a).

Therefore, the first improvement in DUCTROT-M computer program was to take into account this difference in the dimensions of plastic zones of the flange and web.

The second improvement refers to the rotation point of web plastic mechanism. The following cases are studied, considering the beam-column connection details:

- The mechanism type corresponding to the case when the shape of mechanism is limited to the presence of the column flange or vertical ribs (Fig. 5b).
- The formation of web shape plastic deformation is free, having no imposed rotation point (Fig. 5c), in case of plastic hinge formed far from column (cover plates or dog-bone solutions for beam-column connection).

The final version of computer program, DUCTROT-M [2,3,17,18], takes into consideration both of the above cases.

Making use of such shapes, some parametrical studies are performed and the results were published in [19–21].

For the standard beam SB 1 (Fig. 6a), the global plastic mechanism is presented in Fig. 6b. It is composed by two local plastic mechanisms. The mechanisms rotate around the rotation center O. An experimental moment–rotation curve is presented in Fig. 6c. There are some important characteristic points which mark some significant changes regarding beam behavior. The first point A refers to the reaching of the flange yielding; the second one B is defined by the occurrence of fully plastic moment. Moreover, in order to be developed the plastic hinge, the rotation should be increased. At this stage an important observation is that the increasing of bending moment over the fully plastic moment is due to the strain-hardening behavior. The maximum value for moment is reached in point C, when plastic buckling occurs in the yielding zone of the compression flange and web. In this step, the local plastic mechanism is formed. After point C the bending begins to decrease with the increasing of rotation and the equilibrium of the beam becomes unstable. The ultimate rotation

Fig. 5. Experimental aspects of local in-plane plastic mechanisms (modified after [25]): (a) Relation between flange and web lengths of buckled shape; (b) Position of rotation point in case of vertical ribs; (c) Position of rotation point in case of free conditions.
capacity is determined in the lowering post-buckling curve at the intersection with the theoretical fully plastic moment (point O).

The theoretical moment–rotation curve included in computer program must reproduce the above experimental curve. Fig. 7 presents this curve, for which the elastic and plastic behavior can be described by analytical relationships without any problems. The difficulties to complete the moment–rotation curve are related to the plastic post-buckling curve, referring to the degradation of moment capacity due to the plastic buckling. For this purpose, the use of local plastic mechanisms proved to be very operative. The maximum moment results at the intersection of plastic and post-critical curves, eroded by local geometrical and mechanical imperfections. The ultimate rotation results at the intersection of this curve with the line corresponding to fully plastic moment.

The local plastic mechanism shape is shown in Fig. 8a, being composed by plastic zones and yield lines in compression flange (Fig. 8b), web (Fig. 8c) and tension flange (Fig. 8d). The work of a plastic mechanism implies that a larger amount of energy is absorbed in the small area of plastic hinges and zones, therefore the other parts can be neglected. The rigid-plastic analysis is based on the principle of the minimum of total potential energy. The result of this analysis, after some mathematical operations presented in [2], is the post-critical curve of local plastic mechanism, described by the relationship:

\[
M / M_p = A_1 + A_2 \theta^{-1/2}
\]

(1)
The coefficients $A_1$ and $A_2$ contain the mechanical and geometrical characteristics of beams and the shape of plastic mechanism. They are given in [2,3,18].

The post-critical curve depends on geometrical parameters of local plastic mechanism. The length of mechanism is examined in [1], based on theoretical studies and experimental data. The current version of computer program takes into consideration these studies, keeping unmodified the length of plastic mechanism. The influence of other parameters defining the shape of plastic mechanism is presented in Fig. 9. The conclusions of this analysis are:

- The main dimension is the one defining the plastic zones of compression flange and web (Fig. 9a), which presents a minimum in determining the rotation capacity.

- The parameter defining the position of rotation point of plastic mechanism shows a minimum for the position in the tension flange (Fig. 9b).

- The asymmetry of mechanism shape produces an increasing of rotation capacity, the minimum being obtained for symmetric shape (Fig. 9c).

While the minimizing of the post-critical curve in function of the first two parameters is included in software’s capabilities, for the last parameter, which depends on the position of rotation point determined by constructional details (Fig. 10), the characteristic of

![Fig. 9. Geometrical parametrical study [2]: (a) Influence of flange plastic zone; (b) Influence of rotation position; (c) Influence of asymmetry of web plastic shape.]

![Fig. 10. Asymmetry of plastic mechanism [2]: (a) Column without continuity plates; (b) Column with continuity plates; (c) Beam with cover plates.]

![Fig. 11. Determination of ultimate rotation for in-plane plastic mechanism using DUCTROT-M computer program.]

- The parameter defining the position of rotation point of plastic mechanism shows a minimum for the position in the tension flange (Fig. 9b).

- The asymmetry of mechanism shape produces an increasing of rotation capacity, the minimum being obtained for symmetric shape (Fig. 9c).

![Fig. 12. Experimental shape for out-of-plane plastic mechanism: (a) View of plastic mechanism (modified after [26]); (b) Lateral rotation of beam (modified after [27]).]
local plastic mechanism asymmetry must be introduced in performance data.

Fig. 11 shows the determination of in-plane rotation capacity using the DUCTROT-M computer program.

4.2. Out-of-plane local plastic mechanism

This plastic mechanism is characterized by lateral displacements of flanges (Fig. 1b). The experimental shapes of out-of-plane plastic deformation, named S-mechanisms, are presented in Fig. 12 [26,27]. Theoretical studies are given in [1,8,9]. This mechanism type is produced by a free lateral rotation around the vertical axis (Fig. 13). The majority of research works do not take into account the fact that the joint could be restrained by elements to prevent the rotation. However, in practical cases the formation of plastic mechanism also involves the participation of the adjacent column. The Fig. 14 presents details of this deformational condition, in the case when the column presence has no any influence. On the contrary case, see the discussion presented [41]. The plastic mechanism is composed by two plastic zones and yielding lines. The post-critical curve is described by the relationship [2]:

$$M / M_p = B_1 + B_2 \theta^{-1/2} + B_3 \theta^{-3/4}$$

(2)

where the coefficients $B_1$, $B_2$ and $B_3$ are given in [2,3,18]. One can remark that, comparing the Eq. (1), for in-plane mechanism, with Eq. (2), for out-of-plane mechanism, an additional term appears, producing a supplementary degradation in the post-buckling range. The Fig. 15 shows the determination of out-of-plane rotation capacity,

Fig. 13. Out-of-plane plastic mechanisms.

Fig. 14. S-shaped plastic mechanism [2]: (a) General view; (b) Compression flange plastic mechanism; (c) Web plastic mechanism; (d) Tension flange mechanism.

Fig. 15. Determination of ultimate rotation capacity for out-of-plane mechanism using DUCTROT-M computer program.
for the same profile as the one of Fig. 11. Obviously the rotation capacity for out-of-plane is larger than the in-plane one, but the degradation is higher.

4.3. Interaction between in-plane and out-of-plane local plastic mechanisms

The experimental evidences [7] show that in majority of tests the first formed mechanism is the in-plane one, and only in the post-buckling range the beam buckles in out-of-plane, due to considerably weakened of flange rigidity, caused by the plastic deformations. Two cases of interaction were distinguished (Fig. 16):

(i) The intersection of two post-buckling curves takes place under the line \( M/M_p = 1 \), when the rotation capacity is defined by in-plane mechanism.

(ii) The intersection occurs over this line, and the rotation capacity must be determined taking into account the interaction of these two buckling modes and the rotation capacity is defined by out-of-plane mechanism.

It is very well known that the coupling of two buckling forms can increase the influence of imperfections [28]. But this form of coupling belongs to the category of weak interaction in post-critical range. In this case the interaction could be neglected, being covered from the...
scatter caused by other factors with higher influence on rotation capacity than this interaction [29].

5. Local plastic mechanisms for quasi-constant moment

The experimental data for determination the quasi-constant moment are obtained from beams loaded by two loads [9,30,31] (Fig. 17a). The local plastic mechanisms are formed by two symmetric in-plane shapes (Fig. 17b). The typical experimental moment–rotation curve is shown in Fig. 17c. The standard beam to evaluate the rotation capacity is presented in Fig. 18a, while the local plastic mechanism in Fig. 18b. The determination of rotation capacity utilizing the DUCTROT-M is given in Fig. 19. Generally, the rotation capacity for quasi-constant moments is larger than the moment gradient.

6. Definition of rotation capacity

In order to decide if a structural member has or no sufficient ductility and to ensure a suitable response under different loading conditions, the practice requires to define some indicators. As such can be the ductility index or rotation capacity. Concerning these indicators one must recognize that there is no standard definition which is universally accepted by all the specialists. However the most rational definition is related to ultimate rotation [1]. The member ductility is based on the determination of rotation capacity parameter.
R, defined as the ratio between plastic rotation at collapse $\theta_p$ and the elastic limit one $\theta_y$: 

$$R = \frac{\theta_p}{\theta_y}.$$

This definition requires the calculation of ultimate rotation. With the aid of DUCTROT-M it is possible to determine the ultimate rotation at the intersection of post-critical curve with the theoretical fully plastic moment. The software facilitates the evaluation of the available ultimate rotation or alternatively the non-dimensional available rotation capacity under various geometrical, mechanical and loading conditions.

7. Reliability of DUCTROT-M computer program

After the development process of a software the main question that arises is mainly associated to the reliability of the provided results. Accordingly, a comparison between theoretical results and experimental tests reported in the technical literature, is performed. The most important experimental tests are selected in [1,2] ([7,12,32–35]), numbering 81 specimens. A very careful examination of related experimental values was carried out, also considering the possibility of existence of some errors in these results, connected with the following aspects [36]:

(i) Determination of material properties in plastic and hardening ranges are less supervised than the ones in the pre-yielding field.

(ii) Measurement of rotation for elastic and plastic deformations may introduce some errors due to testing arrangements.

(iii) Determination of ultimate rotation at the intersection between the post-yielding curve and horizontal straight line corresponding to full plastic moment results for a very small angle between the two curves. Therefore, the measured values can be determined with important errors.

Generally, in the stability problems, variation of results is very large. For instance, in studies of Nakashima [37] referring to statistical evaluation of steel strength, the coefficient of variation is 0.01–0.13, while for ductility capacity, this coefficient is 0.54–1.35. Consequently, a special methodology for validation of theoretical results must be employed. The correlation between experimental data and numerical results were performed. Applying a step by step analysis the experimental data are processed considering rough, systematic or aleatory errors of measurements [38]. Therefore, making use of this methodology [39], in the first step, the 6 experimental values obvious wrong were eliminated. They are out of rational field, from a group of specimens having the same characteristics they have had values very different from the other ones. For the remaining 75 data (with a variation coefficient of 0.379), there are also some errors which can be connected to the above difficulties in measurements. Based on probabilistic considerations and adopted a relevant trust levels some the errors are recognized and eliminated. Furthermore, the mean value, standard deviation and coefficient of variation are determined. The elimination of wrong values is performed in two steps, firstly 15 and secondly 5 data are excluded until a proper trust level of $P = 0.95$ as well as a coefficient of variation 0.185 was obtained. The remaining 55 data offer a high level of correspondence between experimental and theoretical results.

The correlation between the available experimental results, $RE$, and the calculated rotation capacity, $RC$ (using the DUCTROT-M computer program) in given in Fig. 20a (for [7,10] experimental data) and 20b (for [32–35] experimental data). A distinction between in plane and out-of plane mechanisms as reported form experimental evidence is considered in statistical processing. It is remarked that, in spite of a scatter area specific for the stability experimental data, the correlation is good, giving confidence in the developed local plastic mechanism as a methodology for determining the available rotation capacity.

With respect to the type of local plastic mechanism it should be underline that the great majority of experiments (especially for rolled sections) show an out-of-plane mechanism. This fact is also confirmed by the numerical tests performed in [40], where the results came by FEM analysis revealing that the dominant type of plastic buckling for rolled standard beams is the out-of-plane collapse mechanism. This is mainly due to the presence of a simple reinforcement situated under the force, which has very weak torsional rigidity, allowing the lateral displacements of buckled flanges in report with the beam vertical axis.

8. Conclusions

The paper presents the progress of some issues developed in [1] concerning the plastic collapse mechanism approach in determining the available rotation capacity for wide-flange beams. It is described the phenomenological inelastic behavior of the steel elements as observed in experiments. Based on buckled shapes which are formed by plastic zones and yielding lines some collapse mechanisms are discussed. By a continuing improvement of those mechanism shapes and after a long evolution a more advanced computer program the DUCTROT-M is developed taking into account geometrical, mechanical and loading parameters. In this way the paper is devoted to the interpretation and modeling of the buckled shapes captured from experimental evidence and furthermore investigated the improvements as well as revalidated the models presented in [1]. Based on those mechanisms in the companion paper [41] the application in practical aspects of the DUCTROT-M will be presented. Through parametrical studies on welded and rolled wide-flange steel beams the available ductility under monotonic conditions were investigated demonstrating the capabilities of the software to quantify the inelastic capacity of such elements.

References


