

Finite element analysis of local buckling of steel-concrete continuous composite beams

*KHATIR Abdelwahhab¹⁾ and TEHAMI Mohamed²⁾

^{1), 2)} *Civil Engineering Department, University of Sciences and Technology of Oran
Mohamed Boudiaf (USTO-MB), BP1505 Oran El M'Naouer 31000, Algeria*
¹⁾ abdelwahhabkhatir@gmail.com

ABSTRACT

For continuous steel-concrete composite beam with the slab rests directly on the metal profile, in negative moment, an important part of the web is subject to compressive stresses, hence the buckling limiting the ability of rotation of the cross section, thus preventing to reach its ultimate strength. An analytic model calculation, based on a failure mechanism, to evaluate with sufficient precision the rotation capacity to the right of the intermediate support depending on the moment evolution, has been developed by (Tehami 1997) and justified by experimental results of tests carried out by the same author at INSA Rennes (France) and its confrontation with other models proposed in the literature.

In the present work we investigated, using a numerical method based on finite element, the proposed model by reference (Tehami 1997) on the local buckling of steel-concrete continuous composite beams. Indeed, and in an effort to learn more about the phenomenon of local buckling of steel-concrete continuous composite beams, a finite element analysis was performed on this model (Tehami 1997) using the ABAQUS code. Then this work focuses on numerical simulation, based on different modeling assumptions in order to obtain moment-rotation relationship. A comparison with previous work found in the literature was made.

Keywords: buckling, steel-concrete composite beam, finite element, compression, moment-rotation.

1. INTRODUCTION

Several technical fields such as aerospace, mechanical and civil engineering use now common enough thin panels. In recent decades, several studies have been conducted to describe the deformation due to the uniform compression (Bulson ; Timoshenko and Gere ; Lu, Newaz et al. 2005), tension (Friedl, Rammerstorfer et al. 2000; Brighenti 2005) and shear (Timoshenko and Gere) for such structures.

¹⁾ Graduate Student

²⁾ Professor

In a steel-concrete continuous composite beam, when the concrete slab is in tension and the bottom flange of the steel beam is in compression under bending moments, the buckling is inevitable to occur and that will limit the full capacity of the beam to expand. The modes of buckling in continuous composite beams can be either local or lateral-distortional that is characteristic of lateral buckling of the compression flange accompanied with distortion out of the plane of the web, near internal supports. This mode of buckling does not use the usual assumption of Vlasov that the cross section remains undeformed. There was extensive research on the buckling of composite beams in negative bending. Literatures can be found and summarized in (Bradford and Kemp 2000; Ronagh 2001). The first rule of design for the global buckling of composite beams based on a rational buckling analysis is presented in (Johnson and Fan 1991). Then, the design rules for both local and distortional buckling were developed by (Bradford and Johnson 1987) based on inelastic finite element analysis and finite band.

In the process of British composite bridges (BSI 1980), the calculation of the critical buckling stress of a continuous composite beam is related to the effective slenderness of the bottom flange resting on an elastic spacer retained laterally. This effective slenderness was later modified by (Weston, Nethercot et al. 1991) into account the distortion of the web based on elasto-plastic finite element parametric study of 24 continuous composite beams with a large variation in the slenderness of the web.

The Eurocode 4 (STN 1994) presents a more sophisticated approach to evaluate the critical buckling moment in which the distortion of the web is modeled using continuous elastic straps. A series of test beam were performed at the University of Warwick (Johnson and Fan 1991; Johnson, CHEN et al. 1993) to study the ruin of buckling of continuous composite beams. It was verified that the buckling modes can be classified into local buckling and distortional retained. The results showed that the interaction between the local and distortional buckling governs the resistance at break of the test samples and is strongly influenced by the initial imperfections. While an analytical and numerical analysis was carried out by a number of researchers (Chai, Babcock et al. 1981; Bolotin 1996; Lin, Cheng et al. 1996; Pavier and Clarke 1996; Cho and Kim 1997; Pradhan and Tay 1998) to analyze laminated composite structures, taking account of their buckling and post-buckling behavior.

In addition, the application of the real stresses distribution is done by authors who have published their works and thus obtained reliable results. (Pavlović and Baker 1983) used an analytical method to study the buckling of thin plates. (Rockey and Bagchi 1970) used the finite element method to study the buckling stiffened, and (Stephen and Steven 1996) worked on the estimation error for the element buckling. (Ikhenazen, Saidani et al. 2010) analyzed the linear buckling problem of simply supported thin plates subjected to non-uniform compression using the finite element method where they found representative results for the coefficient of elastic buckling

The present work deals with the finite element analysis of steel-concrete composite beam and considers, in particular the relationship of moment-rotation of the beam modeled using the ABAQUS code. For the choice of models and based on the literature review, we turned to two types of modeling: analytical models and finite element models (FEM).

This analysis shows that the finite element approach requires more computer equipment and expertise of the engineer, but allows a more comprehensive and

coherent analysis. However, if a more realistic assessment of the behavior of this type of structure is made, the cost is reduced and a higher safety factor generally acquired.

2. COMPOSITE BEAMS THEORY

A theory for the analysis of composite beams in steel and concrete is described below. The following assumptions are made by (Porco, Spadea et al. 1994):

- (1) Materials are elastic;
- (2) Deflections are small;
- (3) Shear deformations are neglected;
- (4) The strains vary linearly both over the steel beam and concrete slab;
- (5) The friction between the steel beam and the concrete slab is negligible;
- (6) The radius of curvature is the same both for the steel and concrete parts;
- (7) The vertical displacements are the same for the two elements.

In Fig.1 a cross-section of a typical composite of steel and concrete is shown together with the system of moments, and shear and axial forces appropriate for the equilibrium

In particular, it is worthwhile noting the shear flow q_c , which must be resisted by the connectors. In Fig. 2 the deflection and axial displacements of the two adjacent parts of the composite beam are depicted at an arbitrary point along the structure. With reference to this figure we can obtain the displacement field of an arbitrary point in the steel beam or in the concrete slab as shown in Eq. (1):

$$u^{(i)}(x, y, z) = u_0^{(i)}(x) + \phi(x)(z - z_{Gi}) \quad (1)$$

$$w^{(i)}(x, y, z) = w^{(i)}(x) \quad (i= 1,2 ; z_{G1} \leq 0 ; z_{G2} \geq 0)$$

By the previous assumptions we can write the Eq. (2):

$$\phi = -\frac{dw}{dx} \quad (2)$$

Because of the assumed elastic linear behavior of the materials, the constitutive Eqs. (3)-(4) are:

$$\varepsilon_{xx}^{(i)} = u_{0,x}^{(i)} - \phi_{,x}(x)(z_G - z_{Gi}) \quad i = (1,2) \quad (3)$$

$$\sigma_{xx}^{(i)} = E^{(i)}\varepsilon_{xx}^{(i)} \quad i = (1,2) \quad (4)$$

Where $E^{(i)}$ the Young's modulus for each element and Z_G is the barycenter position of the entire cross section of the composite beam.

Thus, the slip between the Δs the steel-concrete interface is shown in Eq. (5) as:

$$\Delta s = \left(u_0^{(1)} - u_0^{(2)} \right) + [\phi(z_{G2} + |z_{G1}|)] = \left(u_0^{(1)} - u_0^{(2)} \right) - \left[\frac{dw}{dx} (z_{G2} + |z_{G1}|) \right] \quad (5)$$

The effective interlayer connection is assumed to be represented by the Eq. (6):

$$\Delta s = \frac{q_c l_c}{n_r k_c} \quad (6)$$

Where i_c is the spacing of the connectors, k_c is the shear modulus of the connectors, n_r is the number of rows of the connectors and q_c is the shear flow defined above.

It is clear that the degree of connection of a composite beam is governed by the value of shear modulus k_c . If k_c tends to infinity the case of a beam rigidly connected (complete interaction) is reached, while k_c tends to zero if a non-connected composite beam is resulted.

3. MODELLING OF STEEL-CONCRETE CONNECTION

The most common connectors used in the construction of the steel-concrete composite beams are T, C and stud connectors. In general, these types of connectors for all codes provide only approximate relationships to design and suggest their adhoc experiments to determine their actual behavior. Experimental analysis was performed by (Matildi, Mele et al. 1975), where the connectors have been tested by beams and by push-out patterns. All connectors showed essentially the same behavior, both qualitatively and quantitatively, by classifying all as a rigid type.

Referring to Fig. 3, the actual behavior of the connection can be modeled as elastic perfectly plastic replacing the experimental curve with the bilinear curve.

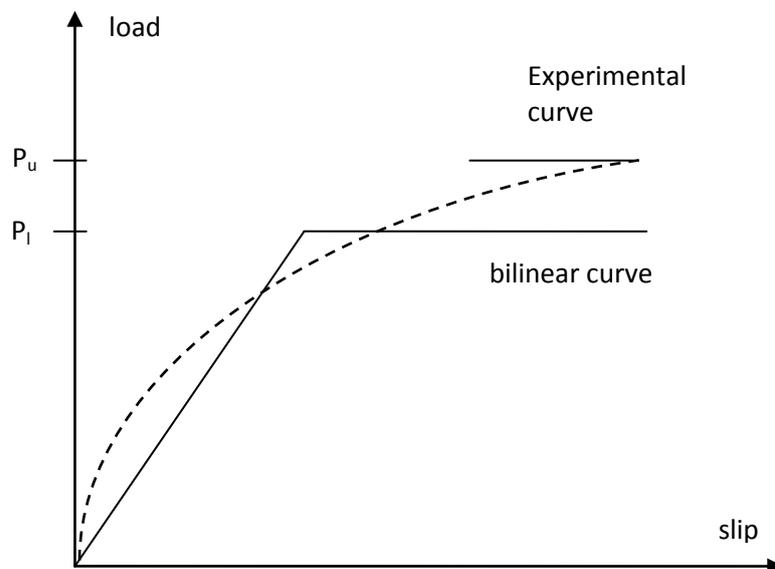


Fig. 3 Actual behavior of interlayer connection

4. PROPOSED ANALYTICAL MODEL

In the present work we consider an analytical model proposed by (Tehami 1997) illustrating a failure mechanism for local buckling of a composite beam whose the cross section is shown in Fig. 4, inspired by experimental observation shown in Fig. 5.

The relationship $M-\theta$ is then derived directly from the equation of work absorbed by the failure mechanism. A similar approach was used by (Climenhaga and Johnson 1972) and recovery by (Ivanyi 1985).

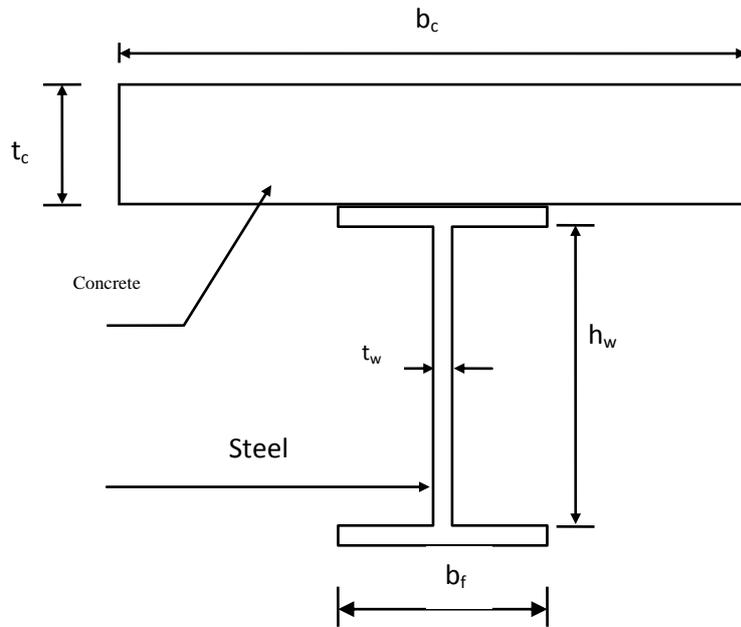


Fig. 4 Cross section of the composite beam

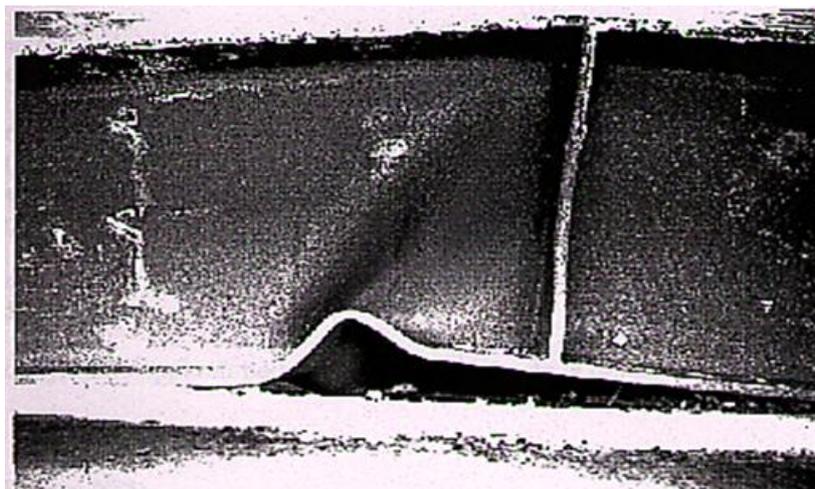


Fig. 5 Failure mechanism observed during the experiment (Tehami 1997)

The Fig. 6 shows a typical curve moment-rotation on support of continuous composite beam found by (Tehami 1997). This curve $M-\theta$ is composed of three sections: (1), (2) and (3).

The section (1) of the $M-\theta$ curve can be determined by simple elasticity theory.

The section (2) has a more convenient approximation of the actual behavior can be provided by the interaction of the $M-\theta$ curve due to local buckling with the horizontal line $M = M_{pl}$

The section (3) of the curve $M-\theta$ is the Moment-Rotation curve due to local buckling of a continuous composite beam. This curve is not defined for values of θ infinitely small.

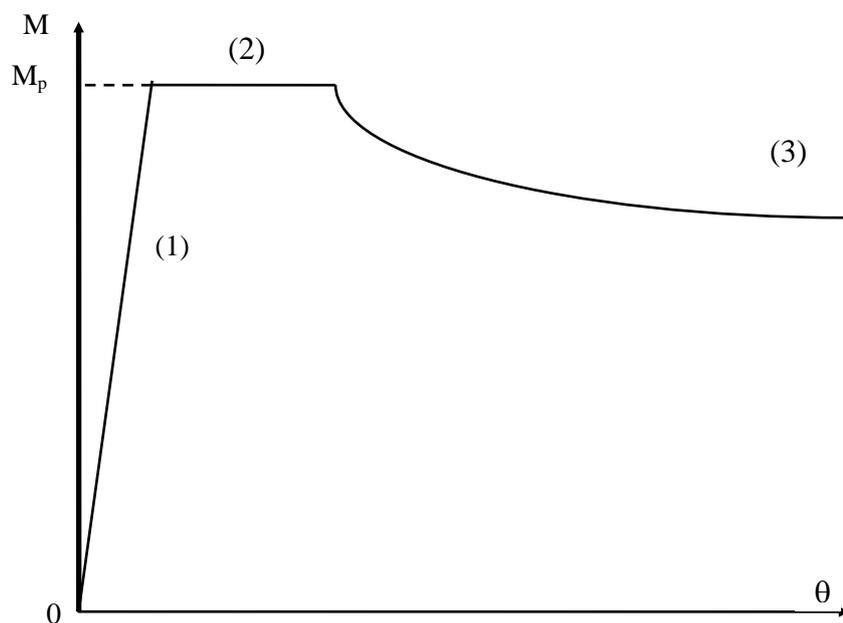


Fig. 6 moment-rotation curve on support of continuous composite beam [1]

5. FINITE ELEMENT MODEL

Using the finite element software ABAQUS (Version 2011) , a finite element model in three dimensions has been developed to simulate the buckling behavior of materials of steel-concrete composite beam with physical and mechanical properties are listed in the table 1

The Support conditions and the concentrated loads applied to the beam are shown in Fig. 7.

Table 1. Physical and mechanical characteristic of materials.

Material	Properties	Values
Concrete slab	Young's modulus (Mpa)	36600
	Poisson's ratio	0.2
	Compressive strength (Mpa)	23.5
Steel girder	Young's modulus (Mpa)	210000
	Poisson's ratio	0.3
	Yield stress (MPa)	280
	ultimate strain	0.1
Reinforcing steel	Young's modulus (Mpa)	210000
	Poisson's ratio	0.3
	Yield stress (MPa)	470

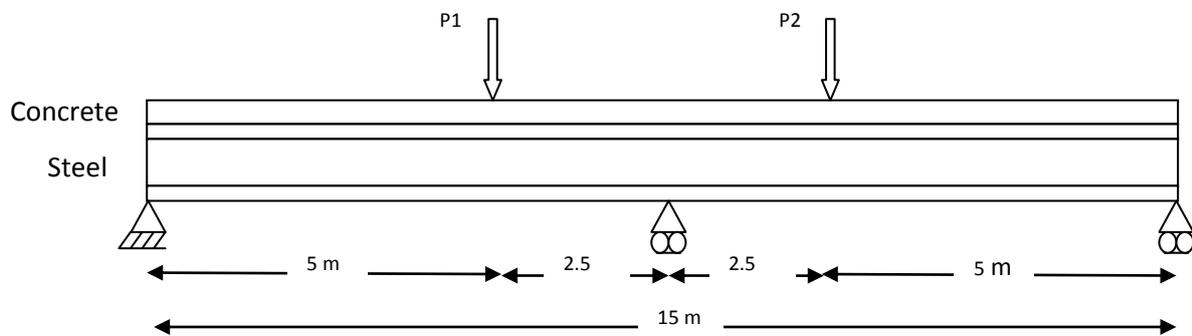


Fig. 7 Support conditions and load applied to the composite beam

The beam is modeled using ABAQUS C3D8 element types with 8 nodes shown in Fig. 8.

A typical finite element mesh (Fig. 9) is used for the analysis of continuous steel-concrete composite beam.

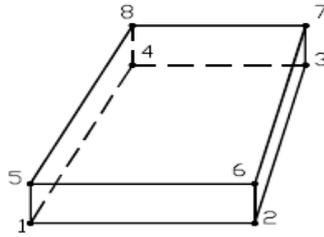


Fig. 8 C3D8 Elément

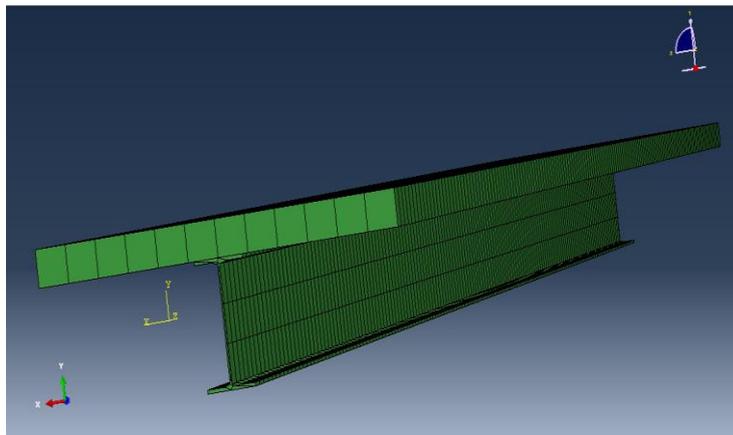


Fig. 9 Mesh of the composite beam

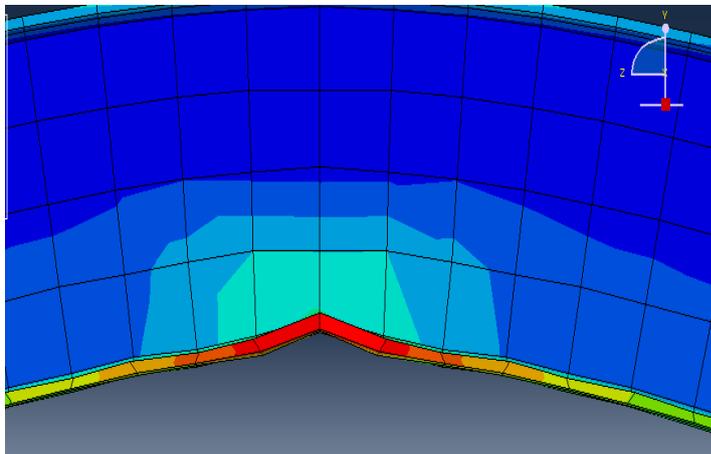


Fig. 10 Mechanism of deformation observed in the finite element model

The mechanism of deformation observed in the ABAQUS code is shown in Figure 10 and appears substantially similar as that observed in experimentation done by (Tehami 1997) shown in the previous Fig. 5.

6. MOMENT-ROTATION RELATIONSHIP

The issue of the previous model was to produce a graph moment-curvature. To do that, the output data must be obtained and analyzed. For the resultant moment of force, the internal energy values are used to calculate values of moment. It seemed like the best way to calculate the moment because the internal energy is an output value by default for all ABAQUS models.

A number of loads of different magnitude is applied to the beam. Note that charging starts at 150 KN and increases by an increment of 20 KN.

The vertical displacements and the internal energies calculated ABAQUS were used to calculate successively the rotational angle at the intermediate support and the moments.

Because of the high non-linear distortion of the beam, the equation for calculating the moment takes into account the plastic zone of moment-rotation relationship. The moment was calculated based on Eq. (15):

$$Energy = M(\theta_2 - \theta_1) \quad (15)$$

Where :

M : is the moment in KN.m

θ : is the rotational angle in Radians

Simplifying the Eq. (15) and solve for the moment.

$$M = \frac{dE}{d\theta} \quad (16)$$

Figs. 11-12 show the variation of the energies and moments as a function of rotation.

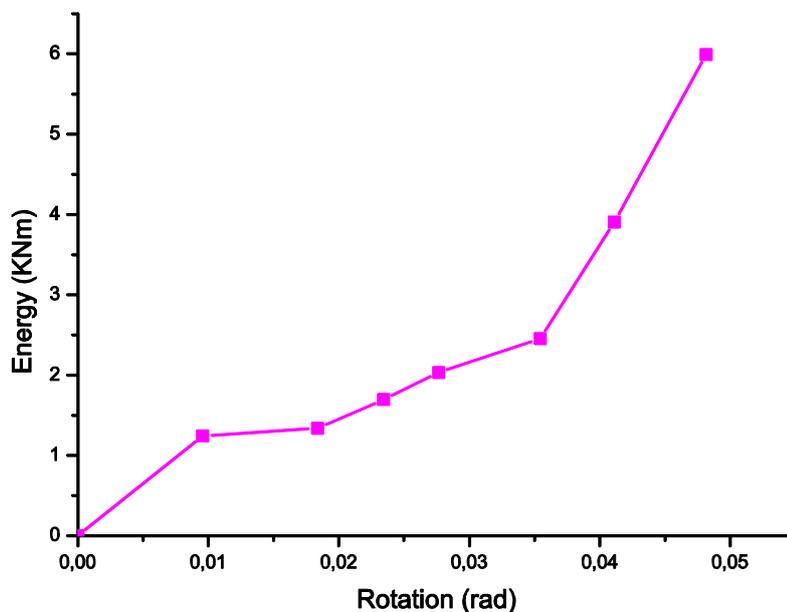


Fig. 11 Curve internal energy as a function of rotation

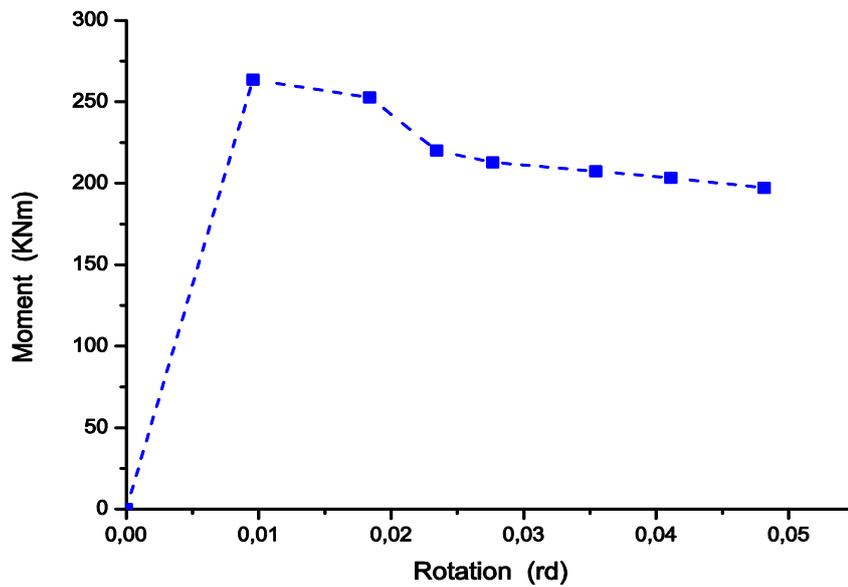


Fig. 12 Moments-rotation curve

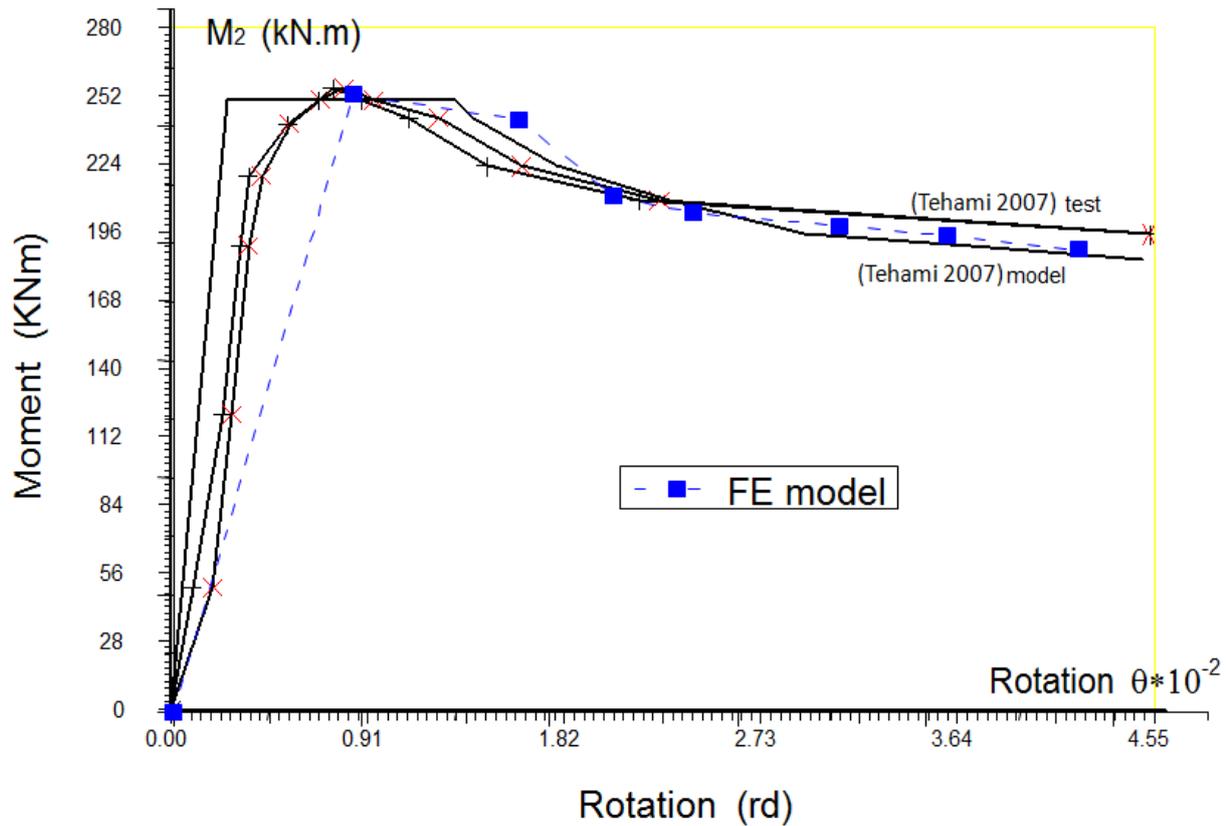


Fig.13 Curves $M-\theta$ experimental, theoretical (Tehami 1997) and finite element of the continuous composite beam

7. JUSTIFICATION OF THE MODEL COMPARED WITH OTHER MODELS

To get support of validity, the finite element model proposed will be compared with other models of computation.

The model studied in this comparison is that of (Tehami 1997) which is an analytical model justified by experimentation. This model presents a similar approach to that of finite element as seen in the Fig. 13.

We see in Fig. 13 that the curve representing the finite element model is clearly closer to the experimental curve (Tehami 1997), and that is both bending moment and rotation capacity.

8. CONCLUSIONS

The enhanced and efficient model proposed in this paper is able to predict the behavior of steel-concrete continuous composite beams taking into account the moment-rotation relationship in the case of buckling phenomenon.

Based on the theory of plastic limit, a failure mechanism, responsive as possible to the given experimental observation available in the literature, is presented for the buckling of the cross section.

The result of this work is to come to the determination of a curve represents the moment-rotation relationship which was confronted with the experimental curve given by the model (Tehami 1997). This comparison gave us a proper justification and validity for the proposed finite element model.

REFERENCES

- Bolotin, V. V. (1996). "Delaminations in composite structures: its origin, buckling, growth and stability." *Composites Part B: Engineering* **27**(2): 129-145.
- Bradford, M. and R. Johnson (1987). *Inelastic buckling of composite bridge girders near internal supports*. ICE Proceedings, Thomas Telford.
- Bradford, M. and A. Kemp (2000). "Buckling in continuous composite beams." *Progress in Structural Engineering and Materials* **2**(2): 169-178.
- Brightenti, R. (2005). "Buckling of cracked thin-plates under tension or compression." *Thin-Walled Structures* **43**(2): 209-224.
- BSI, B. (1980). "5400 Steel, concrete and composite bridges, Part 10: Code of practice for fatigue." British Standards Institution.
- Bulson, P. "The stability of flat plates, 1970." Chatto and Windus, London.
- Chai, H., C. D. Babcock, et al. (1981). "One dimensional modelling of failure in laminated plates by delamination buckling." *International journal of solids and structures* **17**(11): 1069-1083.
- Cho, M. and J.-S. Kim (1997). "Bifurcation buckling analysis of delaminated composites using global-local approach." *AIAA journal* **35**(10): 1673-1676.
- Climenhaga, J. J. and R. P. Johnson (1972). "Moment-rotation curves for locally buckling beams." *Journal of the Structural Division* **98**(6): 1239-1254.

- Friedl, N., F. G. Rammerstorfer, et al. (2000). "Buckling of stretched strips." *Computers & Structures* **78**(1): 185-190.
- Ikhenazen, G., M. Saidani, et al. (2010). "Finite element analysis of linear plates buckling under in-plane patch loading." *Journal of Constructional Steel Research* **66**(8): 1112-1117.
- Ivanyi, M. (1985). "THE MODEL OF THE" INTERACTIVE PLASTIC HINGE"." *Civil Engineering* **29**(3-4): 123-146.
- Johnson, R., S. CHEN, et al. (1993). "STABILITY OF CONTINUOUS COMPOSITE PLATE GIRDERS WITH U-FRAME ACTION." *Proceedings of the ICE-Structures and Buildings* **99**(2): 187-197.
- Johnson, R. and C. Fan (1991). *Distortional lateral buckling of continuous composite beams*. ICE Proceedings, Thomas Telford.
- Lin, C.-C., S.-H. Cheng, et al. (1996). "Local buckling of delaminated composite sandwich plates." *AIAA journal* **34**(10): 2176-2183.
- Lu, J., G. M. Newaz, et al. (2005). "Buckling strength analysis of adhesively bonded aluminum hat sections." *International journal of solids and structures* **42**(18): 4947-4957.
- Matildi, P., M. Mele, et al. (1975). *Analisi sperimentale e criteri di calcolo dei collegamenti trave-soletta nelle strutture composte di acciaio e calcestruzzo*, Istituto di Scienza delle Costruzioni.
- Pavier, M. and M. Clarke (1996). "A specialized composite plate element for problems of delamination buckling and growth." *Composite structures* **34**(1): 43-53.
- Pavlović, M. and G. Baker (1983). "Buckling of non-uniformly compressed plates." *Theoretical and Applied Mechanics, Transactions of Yugoslavian Society of Mechanics* **9**: 91-104.
- Porco, G., G. Spadea, et al. (1994). "Finite element analysis and parametric study of steel-concrete composite beams." *Cement and Concrete Composites* **16**(4): 261-272.
- Pradhan, S. and T. Tay (1998). "Three-dimensional finite element modelling of delamination growth in notched composite laminates under compression loading." *Engineering fracture mechanics* **60**(2): 157-171.
- Rockey, K. and D. Bagchi (1970). "Buckling of plate girder webs under partial edge loadings." *International Journal of Mechanical Sciences* **12**(1): 61-76.
- Ronagh, H. R. (2001). "Progress in the methods of analysis of restricted distortional buckling of composite bridge girders." *Progress in Structural Engineering and Materials* **3**(2): 141-148.
- Stephen, D. and G. Steven (1996). "Error estimation for plate buckling elements." *Computers & Structures* **61**(4): 747-761.
- STN, E. (1994). *2: Eurocode 4: Design of composite steel and concrete structures, Part*.
- Tehami, M. (1997). "Local buckling in class 2 continuous composite beams." *Journal of Constructional Steel Research* **43**(1): 141-159.
- Timoshenko, S. and J. Gere "Theory of elastic stability. New York: McGraw-Hill, 1961."
- Version, A. (2011). "6.10 EF." *User Documentation, Dassault Systems*.
- Weston, G., D. Nethercot, et al. (1991). "Lateral buckling in continuous composite bridge girders." *Structural Engineer* **69**(5).