3D NON-LINEAR MODELING BEHAVIOUR OF STEEL-CONCRETE COMPOSITE SIMPLY SUPPORTED BEAMS UNDER THREE-POINT BENDING STRESS

Ghenam Abada[1*], Mohamed Tehami[2] and Abdelrahmane Bekkadour Benyamina[1]

[1,2] Department of Civil Engineering, Sciences and Technology University (USTO), Oran, Algeria.
[1] Department of Civil Engineering, Faculty of Applied Sciences, Ibn Khaldoun University, Tiaret, Algeria.
Emails: abadagh@yahoo.fr , mohamedtehami@yahoo.fr, beny104@gmail.com

*Corresponding Author

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ABSTRACT

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This paper presents a 3D non-linear numerical model, developed to predict the mechanical behaviour of simply supported steel-concrete composite beams under three-point bending stress.
Using on Abaqus software a 3D model is created, which takes into account all the elements of the steel-concrete composite beam. The concrete slab, steel beam, and studs are modeled using solid elements, reinforcing bars are neglected. The geometrical and mechanical characteristics are based on beams tested in previous studies. The non-linear behaviour of steel-concrete materials is considered and the interaction between the different surfaces is taken into account.
The deflection and slip results at the interface of slab and steel sections showed good agreement with experimental and analytical results. The maximum load value is close to that obtained by a plastic analysis of the composite section according to the Eurocode (1994) rules, with a relative deviation of 10%. Furthermore, the behaviour of increasing the reinforcing plate thickness on the composite beam gives an increase in maximum load and a decrease in the slip at the steel-concrete interface.

Keywords: Composite beam, connectors, connection, tests, push-out, 3D modeling.

INTRODUCTION

The specificity of composite element is due to the mechanical association of two materials of different natures and properties, steel and concrete, through a connection at the interface level of the materials, which increases both the rigidity and the resistance of the element. Many structural and economic advantages that can be derived from this association, these advantages have been among

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the main factors that have allowed the development of structure in both the building and civil engineering structures.

A large number of FEM models dealing with different aspects of composite beams behaviour exists in the literature. The oldest ones are models where the steel beam and the slab are represented by beam elements connected with different interaction hypotheses to represent the connection. Two- and three-dimensional models are more recent and especially fewer in number.

The firsts models of this type date back to the 1980s, Arizumi and Hamada (1981) have developed a 2 node beam element with 3 degrees of freedom per node. However, this element can only model a uniformly distributed connection between steel and concrete.

In France in 1995, (Xu, 1995) has described a composite beam model, which uses two Bernouilli-type beams, connected by connecting elements with a non-linear load-slip behaviour law. The behaviour of the connector is thus characterized by a secant stiffness, which is a function of the slip.

The numerical modeling of the behavior of connectors, through the simulation of Push-Out tests, has been the subject of numerous studies. Many researchers interested in investigation of the behavior of connectors, through the simulation of Push-Out tests; (Qingtian et al., 2014) studied the static behaviour of multi-row stud shear connectors in high- strength concrete (Xiao et al., 2015) analyze the shear behavior of multi-hole perfobond connectors in steel-concrete structure. Yousefi and (Ghalehnovi, 2017) used Push-out test on the one end welded corrugated-strip Connectors in steel-concrete-steel sandwich structure. Recently (Ghenam et al., 2019) investigated the simulations of push-out tests: influence of several parameters and structural arrangements.

Generally, the steel-concrete connection is represented either by discrete elements or as a continuous connection. The discrete elements, which are used to represent the studs, are longitudinal and vertical springs, bars, or trusses (Figure 1).

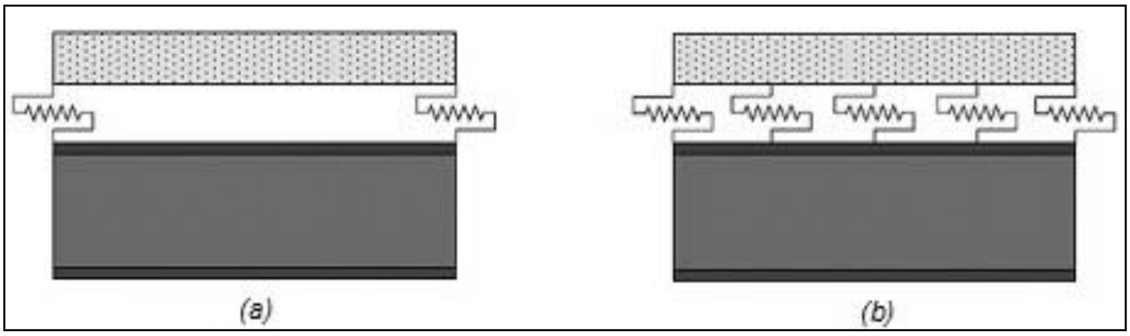

Figure 1. Models with connection formulation : a) discrete b) continuous

Developments in the field of strengthening have allowed the implement of new methods such as the application of repair products, shotcrete, external prestressing, additional prestressing and steel plate bonding. In last years, steel plate reinforcement has been replaced by composite reinforcement. Repair techniques and reinforcement by bonding plates of composite materials called Fiber Reinforced Polymer (FRP) are characterized by their simple implementation, their high tensile strength and good corrosion resistance.

Recently, carbon nanotubes become a new class of reinforcement fibres in polymer matrix composites due to their excellent mechanical, electrical and thermal properties and they took a considerable research interest in the field of materials engineering. Guessas et al. 2018 studied the critical buckling load of reinforced nanocomposite porous plates. Zerrouki et al., (2020) investiged the Critical buckling analyses of nonlinear FG-CNT reinforced nano-composite beam. (Ammar et al., 2020) analyze the buckling of carbon nanotube reinforced composite plates supported by Kerr foundation using Hamilton's energy principle.

A 3D modelling usually allows the exact geometry of the structure to be represented. The model hence created is quite demanding in terms of calculation cost and requires sufficiently powerful computer support. Models using solid elements have been presented by (Zhou, 2003; Baertschi, 2005). The model developed by Baertschi (2005) is used for parametric studies of steel-concrete composite beams with a low degree of connection.

In order to study the real behaviour of steel-concrete composite beams, a 3D model is developed based on beams tested by Chapman (1964) and studied analytically by Muhanned et al. in 2005. This behaviour is characterized by the variation of the mid-span deflection and the variation of the slip at the steel-concrete interface along the beam.

MATERIALS AND METHODS

1. 3D Modeling of a simply supported composite beam stressed in three-point bending

a. Beam geometry

A specimen of steel-concrete composite beam tested by Chapman (1964) spans of 5500 mm. Stud connectors with a diameter of 12.5 mm and a height of 50 mm are spaced 110 mm apart, the steel beam is an IPE profile and the concrete slab is 1220 mm wide and 153 mm thick. The number of stud rows of connectors is 2 (Figure 2.1).

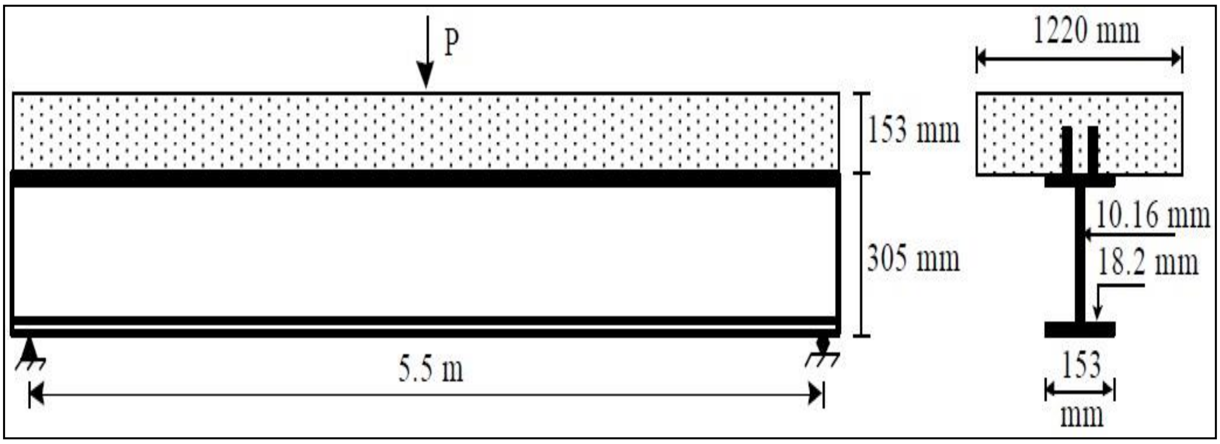

Figure 2.1. Geometrical dimensions of the composite beam

b. Material Properties

- Concrete

For concrete in compression, the stress-strain diagram proposed by BS 8110 (1985) is used, as shown in (Figure 2.2a), the ultimate strain, ϵ_{cu} is limited to 0.0035, the curved part of the stress-strain diagram is defined by equation (1.a):

$$\boldsymbol{\sigma = 5500\sqrt{\sigma_{cu}}.\varepsilon - 11{,}3x10^6\varepsilon^2} \qquad (1.a)$$

With $\boldsymbol{\varepsilon_0}$ is given by equation (1.b)

$$\boldsymbol{\varepsilon_0 = 2.44x10^{-4}\sqrt{\sigma_{cu}}} \qquad (1.b)$$

and the initial modulus of elasticity is defined by equation (1.c):

$$\boldsymbol{E_i = 5500\sqrt{\sigma_{cu}}} \qquad (1.c)$$

Where σ_{cu} is the characteristic strength of concrete equal to 50MPa.
The tensile strength of concrete is relatively low and will be neglected.

- Steel

A stress-strain bilinear diagram for the adopted type of steel as shown in (Figure 2.2b). In this stress-strain diagram, the yield strength, f_y, in tension and compression is the same and equal to 265 MPa. The Young's modulus equals to 205,000 MPa and the strain-hardening exponent is 0.022.

- Connectors

Many load-slip diagrams have been proposed for shear stud connectors, one of them is the exponential; diagram which remains the best of these models. The adopte load-slip diagram for shear connectors is that suggested by Al-Amery and Roberts (1990), (Figure 2.2c). It is represented by the following relationship (2):

$$\boldsymbol{Q = Q_u.(1 - Exp(-\alpha u_{ab}))} \qquad (2)$$

Where Q_u is the ultimate shear strength of stud connector and α is a constant that can be determined from experimental tests, as shown in Figure 2.2c. For the present model Qu=59 kN and α=-3.1265 are used.

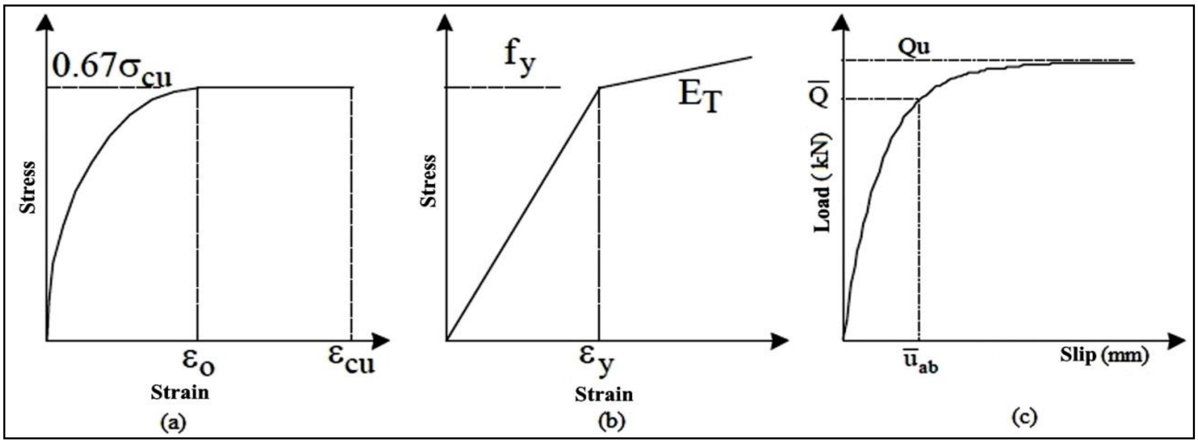

Figure 2.2. (a) Concrete stress-strain diagram (b) Bilinear stress-strain diagram of steel (c) Load-slip diagram of connectors

c. 3D modeling of the beam

Using the symmetry conditions, only the section and span halves are represented in the model, (Figure 2.3a) and (Figure 2.3b). The symmetry conditions according to Z and X axes are applied at mid-span and mid-section respectively (Figure 2.3c).

The steel beam and concrete slab are modeled by linear solid elements. Reinforcement bars in the concrete are not modeled. The overall model consists of approximately 28794 elements and 39596 nodes, (Figure 2.3a). Average compressive strength of the concrete is the point force applied in the middle of the beam, it is replaced by an imposed downward displacement of 200 mm.

In this study, the metal beam-slab interface is modeled by a frictionless sliding contact. Between the shear stud and the slab, the contact is sliding with a coefficient of friction equal to 0.4 (value of Eurocode 2, 2005).

The ABAQUS software (2009) is used to solve the problem.

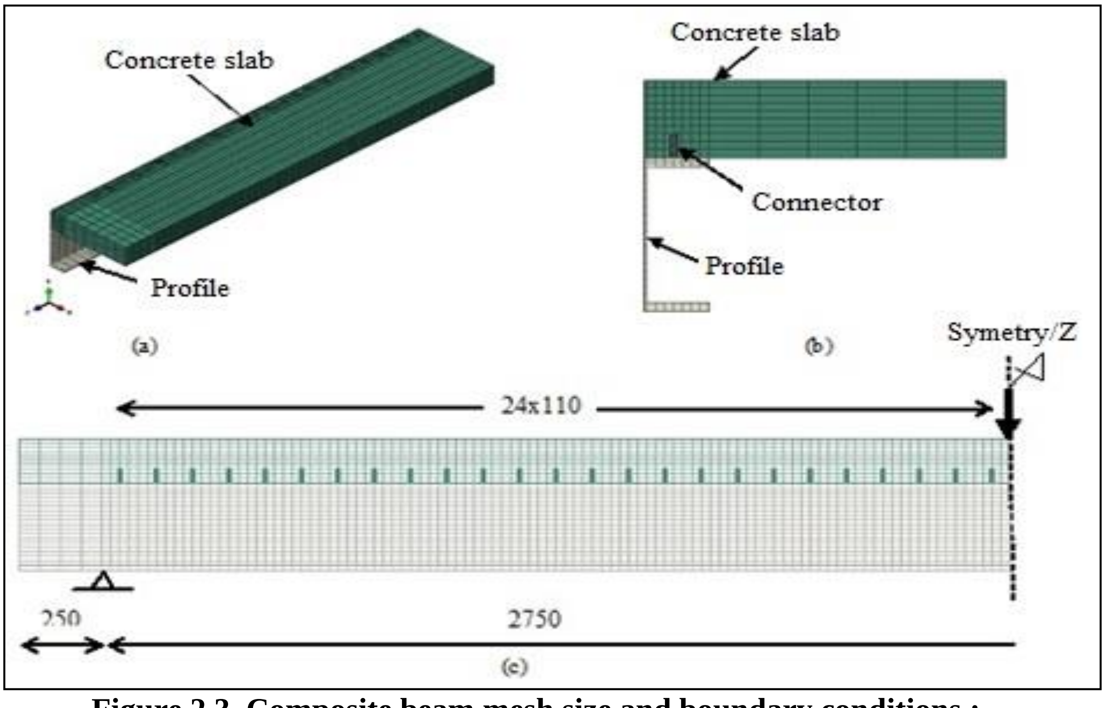

Figure 2.3. Composite beam mesh size and boundary conditions : (a) 3D view (b) Section view (c) Elevation view.

d. Limit load calculation according to Eurocode 4

The ultimate limit load is determined as a function of the resistance moment of the section by the relation (3.a):

$$M_{Rd} = \frac{P_u L}{4} \quad (3.a)$$

which results in (3.b):

$$P_u = \frac{4M_{Rd}}{L} \quad (3.b)$$

RESULTS

Evaluation of the connection degree

The number of connectors required between the section where the positive moment is maximum and the support, for the connection to be complete, is defined by equation 4:

$$N_L = {V_L}/{P_{Rd}} \quad (4)$$

With P_{Rd} given by the relation (5):

$$P_{Rd} = min \begin{cases} 0.8\, f_u.\pi \dfrac{d^2}{4}.\dfrac{1}{\gamma_v} \\ \dfrac{0.29.\alpha.d^2\sqrt{f_{ck}.E_{cm}}}{\gamma_v} \end{cases} \quad (5)$$

And V_L given by the relation (6):

$$V_L = min \begin{cases} F_c = 0.85 f_{cd}.A_c \\ F_a = f_{yd}.A_a \end{cases} \quad (6)$$

Where:

d: Shear stud diameter; $\mathbf{f_u}$**:** Tensile strength of stud material, without exceeding 500 N/mm2 ; $\mathbf{f_{ck}}$**:** Characteristic compressive cylinder strength of concrete at 28 days; $\mathbf{E_{cm}}$**:** Secant modulus of elasticity of concrete.; **α** = 0.2 .[(h/d) +1] for 3£ h/d £ 4 ;**α** = 1 for h/d > 4; **h:** Overall nominal height of a stud connector; $\boldsymbol{\gamma_v}$**:** Partial safety coefficient, is taken equal to 1.25; $\mathbf{f_{cd}}$**:** Equal to fck/γc with γ_c=1.5; $\mathbf{f_{yd}}$**:** Yield strength of steel; $\mathbf{A_c}$ **,** $\mathbf{A_a}$**:** Sections of the slab and the steel beam ; $\mathbf{V_L}$**,** $\mathbf{P_{Rd}}$**:** shear force and design shear strength of a welded head stud.

After all the calculation is done, the degree of connection is defined by equation (7) and equal to :

$$\boldsymbol{\eta = {}^{N}/_{N_L} = \frac{92}{111} = 0.83} \qquad (7)$$

Where N is the number of connectors used and equal to N= 46x2=92

Limit load calculation

The plastic method of Eurocode 4 (1994), (Figure 3) is used to calculate the strength of the steel-concrete composite section in partial connection.
Since $\eta.F_c < F_a$, then the plastic neutral axis is located in the metal beam.
In addition: $\eta.F_c + F_f > F_f + F_w$ then the plastic neutral axis is located in the profile flange.
With: Ff and Fw are respectively the axial forces in the flange and the web of the profile.
The position of the plastic neutral axis xpl is given by equation (8):

$$\boldsymbol{\eta.F_c + b_f.(x_{pl} - t_c).f_{yd} = F_f + F_w + b_f.(t_c + t_f - x_{pl}).f_{yd}} \qquad (8)$$

Which gives: x_{pl} = **162 mm**

The resistance plastic moment of the section is given by equation (9.a) :

$$\boldsymbol{M_{Pl,Rd} = F_a.\left[z_a - x_{pl}\right] + F_f.\left[\frac{x_{pl} - t_c}{2}\right] + \eta.F_c.\left[x_{pl} - \frac{t_c}{2}\right]} \qquad (9.a)$$

Which yields (9.b) :

$$\boldsymbol{M_{Pl,Rd} = 634\ kN.m} \qquad (9.b)$$

and as a result (9.c):

$$\boldsymbol{P_u = \frac{4.M_{Rd}}{L} = 461\ kN} \qquad (9.c)$$

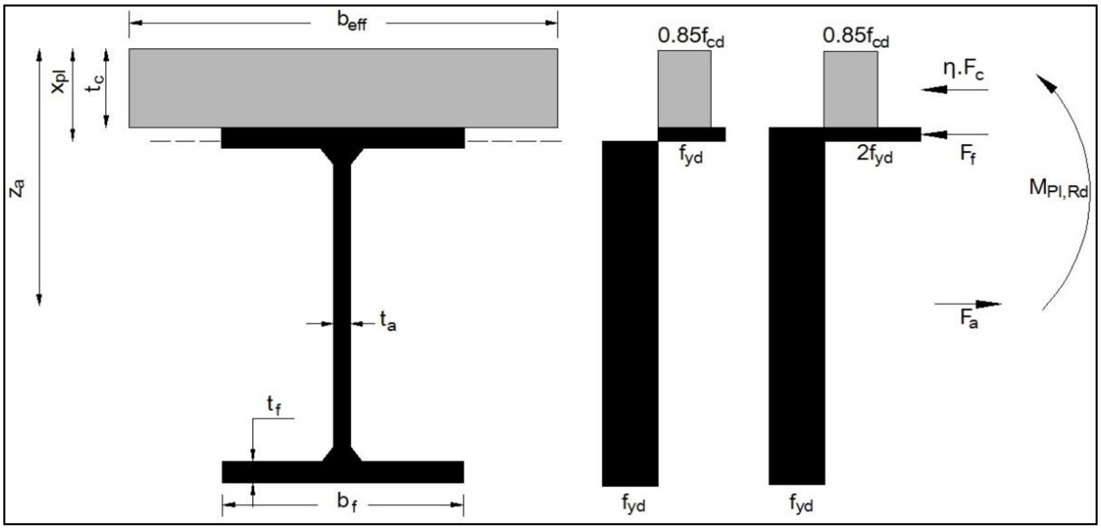

Figure 3. Plastic stress distribution with a neutral axis in the profile top flange.

Effect of the thickness of reinforcing plate on the behaviour of the composite beam

In order to study the effect of reinforcing plate that will be placed on the bottom flange of the steel section, we used the same composite beam, (Figure 4.1).
The length of the plate is 3300 mm, its width is 100 mm and with different thicknesses 7.5 mm, 15mm and 30mm.

A perfect Tie type contact between the two lower plate- bottom flange surfaces and with the plate and the steel profile of the same material type was assumed.

Firstl, a sensitivity study on the plate elements was carried out, i.e., Shell or solids is considered, (Figure 4.2). This study showed that there is no significant influence on the behaviour of the beam (Figure 4.3).

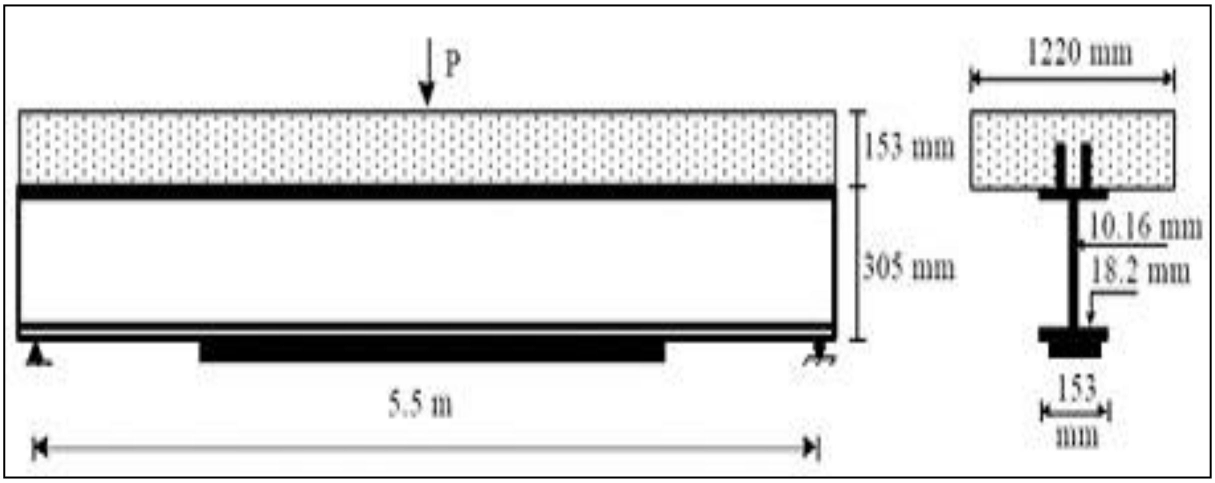

Figure 4.1. Geometrical dimensions of the composite beam with the reinforcing plate.

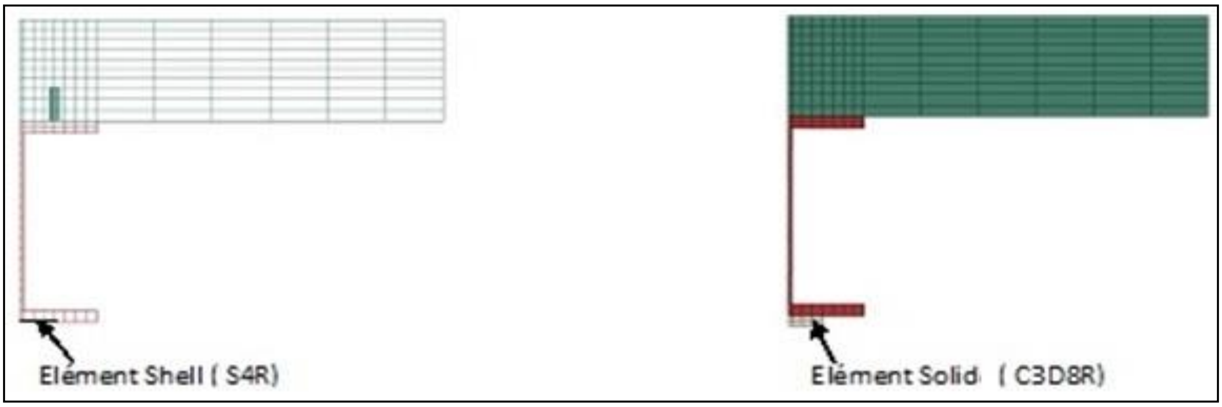

Figure 4.2. Different elements for the reinforcing plate

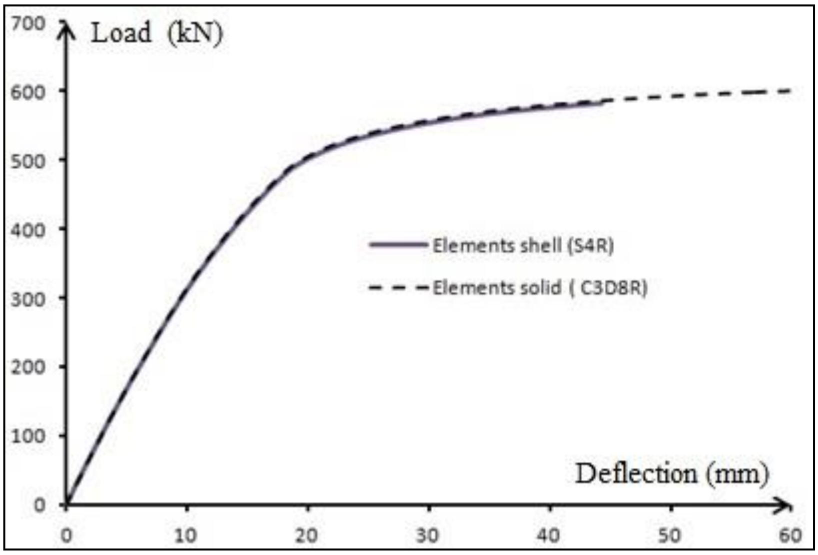

Figure 4.3. Load-deflection curves for different plate elements (thickness = 15mm).

DISCUSSIONS

Discussion of Numerical results

This section aims to investigate the accuracy and efficiency of the **3D non-linear modelling behaviour** of composite steel-concrete beams under three-point bending stress. A simply supported composite steel-concrete beam is considered, the beam is loaded in its middle by a concentrated and partially connected load. As mentioned in the above sections, the finite element analysis is performed using the commercial code (Abaqus, 2009).

The load-deflection curves and slip distribution between the concrete slab and steel beam obtained curves from analyses and tests are shown in (Figure 5.1) and (Figure 5.2) respectively. The set of results obtained for the deflection calculation is in perfect agreement with those obtained from the analytical and experimental analysis. Indeed the 3D numerical calculation, and for a deflection of 75 mm, gives a value of the maximum load equal to 514 kN, the corresponding value given by the analytical calculation is 548 kN and that given by the test of 520 kN with a relative deviation of 6.61% and 1.17% respectively.

Moreover, this value of the maximum load obtained by modelling is close to that given by Eurocode 4 with a relative deviation of 10%.

Concerning the slip distribution at the steel-concrete interface for the same 450 kN load, the following points can be seen that :

- The curves show the same tendency between calculation results.
- Differences are obtained in results because the slip is very sensitive to load changes.
- The maximum value of the slip obtained by the 3D numerical calculation which is 0.559 mm is close to the values 0.563 mm and 0.558 mm obtained by the analytical and experimental analysis respectively.
- The 3D numerical calculation gives at the support level a significant minimum slip compared to the analytical and experimental study.
- The slip is fairly constant along the beam for the 3d numerical calculation, which corresponds well to the distribution of the shear force.

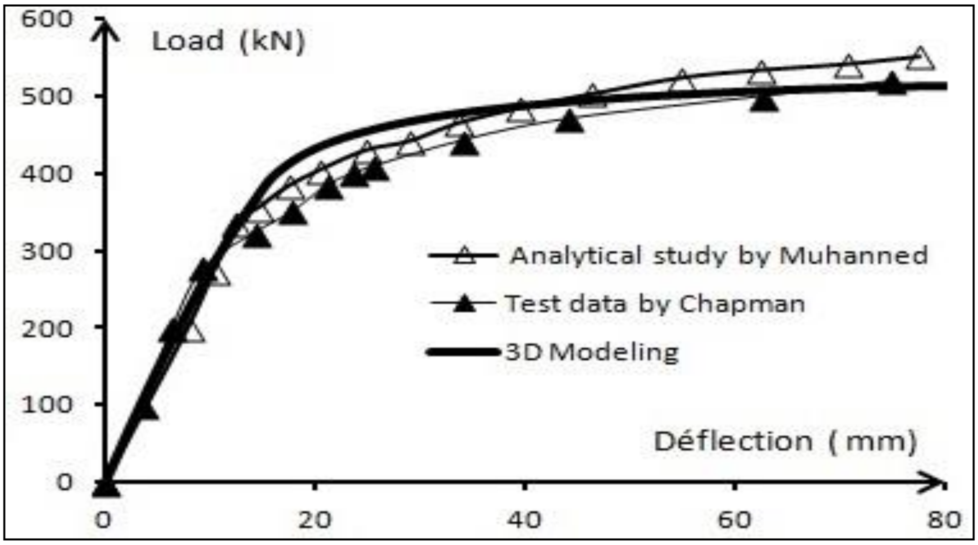

Figure 5.1. Comparison of load-deflection curves.

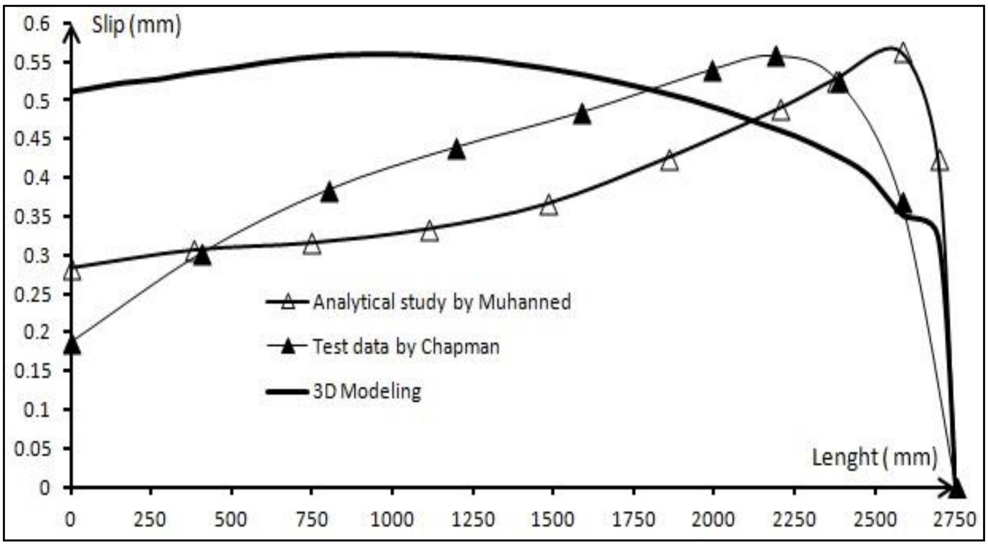

Figure 5.2. Comparison of slip at the steel-concrete interface along the composite beam.

Figures 5.3 and 5.4 show respectively, the load-deflection curves and slip distribution curves between the concrete slab and the steel beam obtained from analytical and numerical analyses, for the same composite beam and different thicknesses of the reinforcement plate.
There is a clear increase in the maximum load of 10%, 16% and 27% for plate thicknesses of 7.5mm, 15mm and 30mm respectively compared to the composite beam without the plate. Moreover, these percentages obtained by our modelling are very close to those obtained by the analytical study.
Concerning the slip distribution at the steel-concrete interface, at the same load of 550 kN there is a clear decrease in the slip with increasing plate thickness. The maximum slip will occur at different locations and its value for each plate thickness is in perfect agreement with the analytical study.

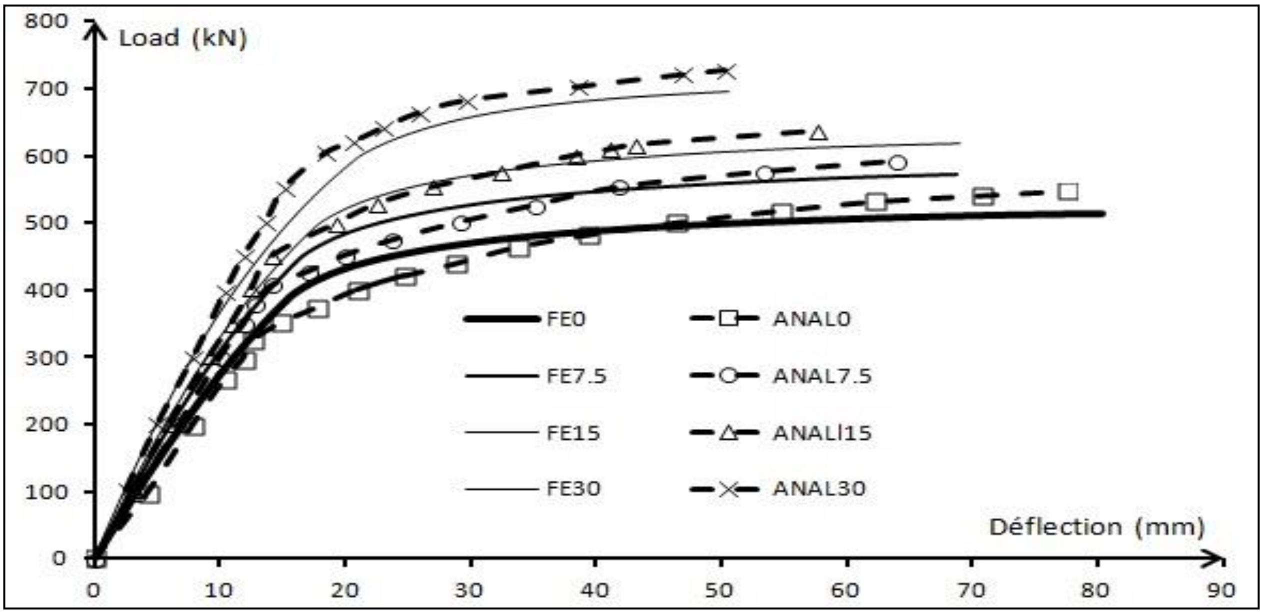

Figure 5.3. Load-deflexion comparaison along the composite beam.

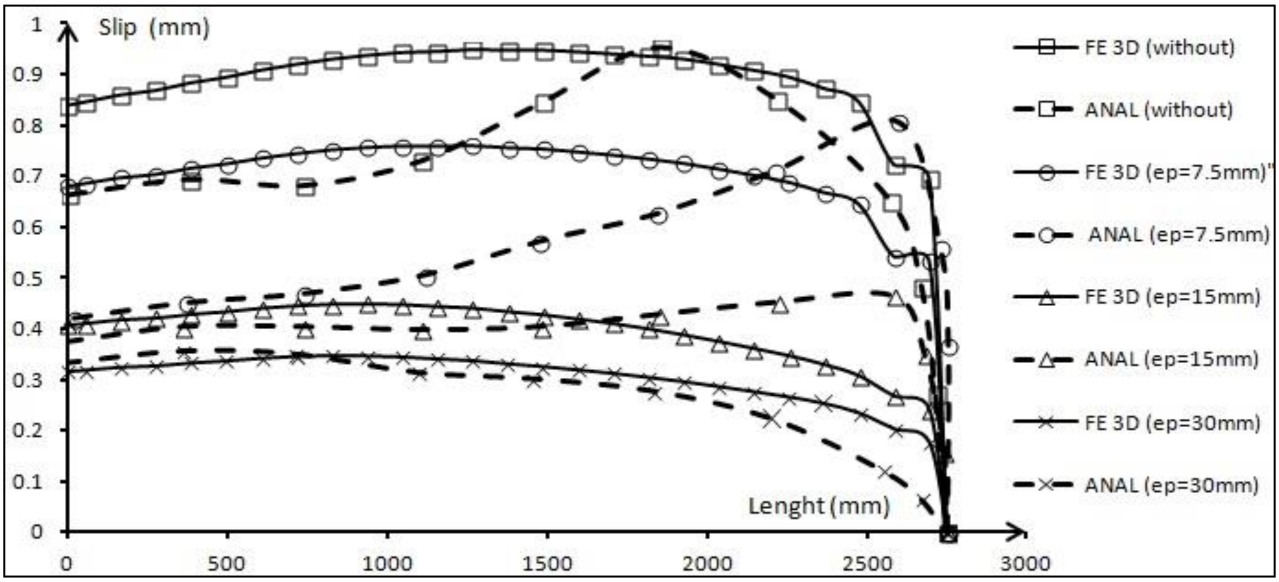

Figure 5.4. Comparison of sliding at the steel-concrete interface with the reinforcing plate along the composite beam.

CONCLUSION

In this work, a modelling of the steel-concrete composite beam with partial connection and concentrated load at mid-span using ABAQUS software is proposed. The load-deflection and load-slip curves obtained are used for comparison between the models proposed in the literature and the experiment.

The resulte show that the 3D numerical model allows a complete non-linear analysis of the behaviour of a composite beam with and without the presence of reinforcing plate. The results obtained are in good agreement with those obtained by the analytical analysis carried out by Shalall and Louis, and the experimental analysis conducted by Chapman (year).

The analysis of the steel-concrete composite beam with the increase in the thickness of the reinforcement plate showed an increase in the maximum load and a decrease in the slip at the steel-concrete interface.

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