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Effectiveness of Slabs in Restraining Lateral Torsional Buckling of Steel Floor Beams

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Abstract: ***This research aims to study experimentally if one could depend on friction forces between beams and slab and on slab in-plane stiffness in resisting lateral torsional buckling of the supporting floor beams. Four scale-down models have been adopted in the experimental work. In the first model, a single beam has been subjected to a uniform pressure to estimate its strength. In the second and third experimental models, concrete slabs have been casted against rough and smooth top flanges respectively. Finally, in the fourth experiential model, concrete slab has been cast against a corrugated metal plate that in turn has been supported on top flange of the beam. This study indicates that friction between slab and top flange of the beam, pressures acting on top flange, and lateral stiffness of slab all of them have large influence in restrain floor beams against lateral torsional buckling.***

Keywords: Stability, Lateral torsional buckling, Steel structure, Non-composite action.

1. Introduction

The continued importance of the research on stability problems is due to the technical and economic developments that demand the use of ever-stronger and ever-lighter structures in an increasingly wider range of applications. The demands of structures with higher strength in addition to lighter weight inevitably lead to a consideration of stability must play a main role in the design [1].

Instability condition occurs where a compression member or structural system loses its ability to resist additional applied loads and shows instead a decrease in load-carrying capacity. In summary, instability occurs at the maximum point of the load-deflection curve [1].

Typically, beams, girders, joists, and trusses designed for flexure have relatively greater strength and stiffness in the plane where the loads are applied than in the plane associated with bending about their minor principal axis. When these sections in not braced laterally in a proper form, they will buckle laterally before reaching their full plastic strength. This buckling mode is usually called the lateral torsional buckling, (LTB), and represents one of limit state of structural usefulness[1].

This paper aims to show the effect of concrete slab in restraining lateral torsional buckling of steel floor beam in non-composite action i.e. without using shear connectors.

2. Review of Literature

2.1 Beam Strength

Lateral torsional buckling is a limit state of structural usefulness where the deformation changes from predominantly in-plane bending to combined lateral deflection and twisting. The final failure pattern involves lateral deflection and twisting in combination with various extents of yielding and flange and/or web local buckling depending on the specific member characteristics [1]as shown inFigure 1.

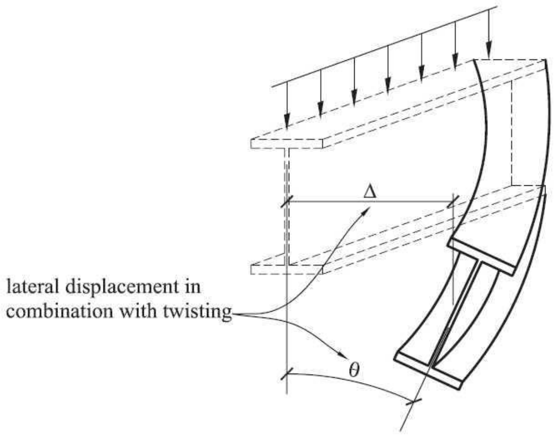

Figure 1 : Lateral-Torsional buckling

As with a compression member, instability can be in an overall sense or it can be local. When a beam bends, the compression region (above the neutral axis) is analogous to a column, and in a manner similar to a column, it will buckle if the member is slender enough. Unlike a column, however, the compression portion of the cross section is restrained by the tension portion, and the outward deflection (flexural buckling) is accompanied by twisting (torsion). Lateral-torsional buckling can be prevented by bracing the beam against twisting at sufficiently close intervals[2].

The moment strength of compact shapes is a function of the unbraced length, L_b, defined as the distance between points of lateral support, or bracing. The relationship between the nominal strength, M_n, and the unbraced length is shown in Figure 2. If the unbraced length is no greater than L_p, to be defined presently, the beam is considered to have full lateral support, andthe nominal moment strength, M_n, is the full plastic moment capacity of the shape, M_p. If L_b is greater than L_p but less than or equal to the parameter L_r , the strength is based on inelastic LTB. If L_b is greater than L_r, the strength is based on elastic LTB.

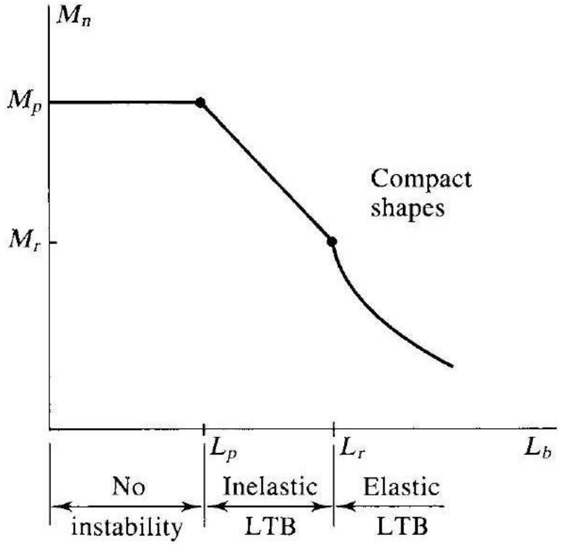

Figure 2 : The relationship between the nominal strength and the unbraced length

The equation for the theoretical elastic lateral-torsional buckling strength can be found in Theory of Elastic Stability [3]. With some notational changes, the nominal moment strength is:

$$M_n = F_{cr} S_x \quad (1)$$

where F_{cr} is the elastic buckling stress and is given by

$$F_{cr} = \frac{1}{L_b S_x}\sqrt{E I_y G J + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w Ksi} \quad (2)$$

where
L_b = unbraced length (in.)
I_y = moment of inertia about the weak axis of the cross section (in.4)
G = shear modulus of structural steel = 11,200 ksi
J = torsional constant (in.4)
C_w = warping constant (in.6)
Equation 2 is valid as long as the bending moment within the unbraced length is uniform (nonuniform moment is accounted for with a factor C_b). The AISC Specification gives a different, but equivalent, form for the elastic buckling stress F_{cr}. AISC gives the nominal moment strength as
$M_n = F_{cr} S_x \le M_p$
where

$$F_{cr} = \frac{C_b \pi^2 E}{(L_b/r_{ts})^2}\sqrt{1 + 0.078\frac{Jc}{S_x h_0}\left(\frac{L_b}{r_{ts}}\right)^2} \quad (3)$$

and
C_b = factor to account for nonuniform bending within the unbraced length L_b.
$r_{ts}^2 = \frac{\sqrt{I_y C_w}}{S_x}$
$c = 1$ for doubly-symmetric I shapes
$c = \frac{h_o}{2}\sqrt{\frac{I_y}{C_w}}$ for channels
h_0 = distance between flange centroids = $d - t_f$
If the moment when lateral-torsional buckling occurs is greater than the moment corresponding to first yield, the strength is based on inelastic behavior. The moment corresponding to first yield is
$M_r = 0.7 F_y S_x$
where the yield stress has been reduced by 30% to account for the effect of residual stress. As shown in Figure 2, the boundary between elastic and inelastic behavior will be for an unbraced length of L_r, which is the value of L_b obtained from the equation of critical stress above when F_{cr} is set equal to $0.7F_y$ with $C_b = 1.0$. The following equation results:

$$L_r = 1.95 r_{ts}\frac{E}{0.7F_y}\sqrt{\frac{Jc}{S_x h_o} + \sqrt{\left(\frac{Jc}{S_x h_o}\right)^2 + 6.76\left(\frac{0.7F_y}{E}\right)^2}} \quad (4)$$

As with columns, inelastic buckling of beams is more complicated than elastic buckling, and empirical formulas are often used. The following equation is used by AISC:

$$M_n = C_b\left(M_p - (M_p - 0.7F_y S_x)\left(\frac{L_b - L_p}{L_r - L_p}\right)\right) \le M_p \quad (5)$$

where the $0.7F_y S_x$ term is the yield moment adjusted for residual stress [2], and

$$L_p = 1.76 r_y\sqrt{\frac{E}{F_y}} \quad (6)$$

2.2 Floor Beam system

In a floor system with a corrugated metal deck, there are steel beams where the deck ribs will run perpendicular to the axis of the beam and steel beams where the deck ribs are parallel with the beams. In building construction, the members that are oriented perpendicular to the span of the slab system are usually referred to as beams, and the members that support the beams and are oriented parallel to the span of the slab system are usually called girders as shown in Figure 3.

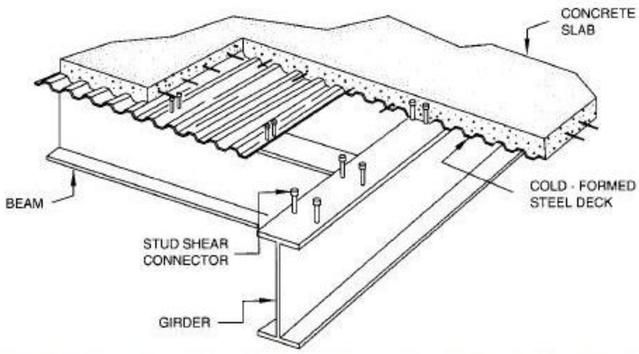

Figure 3 : Floor beams and floor girders

The concrete floor deck can be constructed in various forms, Figure 4 : **Types of composite beams.**Figure 4shows the most common forms of concrete floor deck. In steel structures, the corrugated metal deck is commonly used as shown in Figure 4a. in which its provide a form for wet concrete as well as its adding strength to the overall floor deck system. Another type of floor deck is the reinforced concrete slab shown in Figure 4b which is constructed without corrugated metal deck, this system is more commonly used in bridge construction[4].

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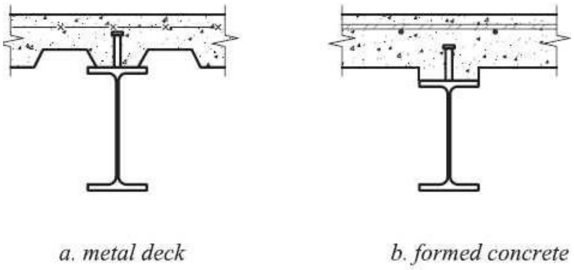

Figure 4 : Types of composite beams.

The beams are treated as a non-composite if the headed studs are not used to engage the concrete slab with the steel beams as shown in Figure 5. By contrast, usually the headed studs are used in floor system, in that case the system is designed as a composite system [4].

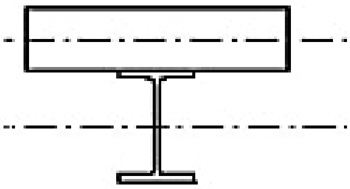

Figure 5 : Non-composite beam

2.3 Composite and non-composite action

Composite action is developed when two load-carrying structural members such as a concrete floor system and the supporting steel beam are integrally connected and deflect as a single unit as in Figure 6b. The extent to which composite action is developed depends on the provisions made to insure a single linear strain from the top of the concrete slab to the bottom of the steel section. The non-composite beam of Figure 6a, wherein if friction between the slab and beam is neglected, the beam and slab each carry separately a part of the load. This is further shown in Figure 7. When the slab deforms under vertical load, its lower surface is in tension and elongates, while the upper surface of the beam is in compression and shortens. Thus a discontinuity will occur at the plane of contact. Since friction is neglected, only vertical internal forces act between the slab and beam[5].

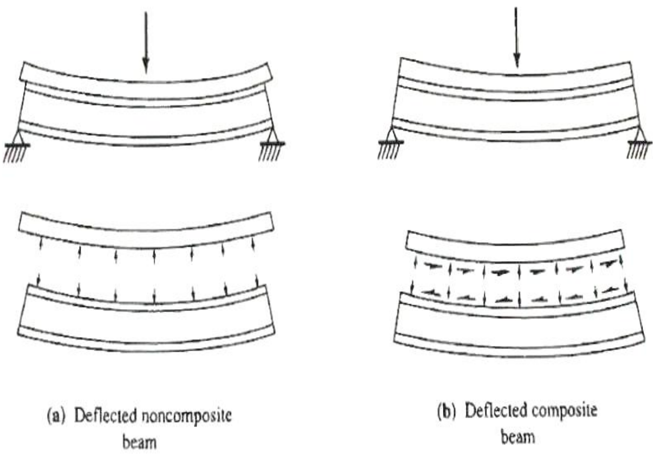

Figure 6 : Composite and non-composite action**.**

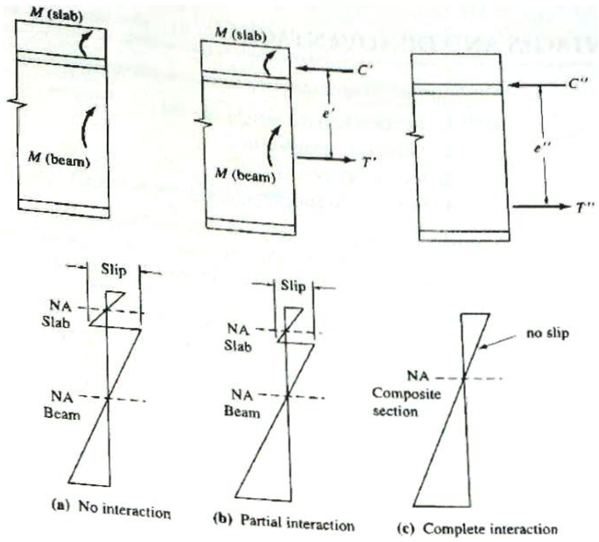

Figure 7 : Strain variation in composite beams**.**

When beam system acts compositely Figure 7 b and c no relative slip occurs between the slab and beam. Horizontal forces (shears) are developed that act on the lower surface of the slab to compress and shorten it, while simultaneously they act on the upper surface of the beam to elongate it[5]. By an examination of the strain distribution that occurs when there is no interaction between the concrete slab and the steel beam Figure 7a, it is seen that the total resisting moment is equal to

$$\Sigma M = M_{slab} + M_{beam} \qquad \textbf{(7)}$$

Its noted that for this case there are two neutral axes: one at the center of gravity of the slab and the other at the center of gravity of the beam. The horizontal slip resulting from the bottom of the slab in tension and the top of the beam in compression is also indicated.

The case where only partial interaction is present as shown in Figure 7b. The slab and the beam neutral axis is closer to each other. The horizontal slip has been decreased, due to the partial interaction. The result of the partial interaction is the partial development of the maximum compressive and tensile forces C' and T', in the concrete slab and steel beam. respectively. The resisting moment of the section would then be increased by the amount $T'e'$ or $C'e'$.

When complete interaction "full composite action" between the slab and the beam is developed, no slip will occurs and the resulting strain diagram can be plotted as shown in Figure 7c. Under this condition. There is a single neutral axis which lies below that of the slab and above that of the beam. In addition, the compressive and tensile forces C'' and T'', respectively, are larger than C' and T' existing in partial interaction. The resisting moment of the fully developed composite section then becomes

$\Sigma M = T''e''$ or $C''e''$[5].

In this work the strength of the steel-concrete beam with non-composite action will be investigated, taking into consideration the frictional forces effect between the concrete slab and the steel beam.

3. The Experimental Work.

3.1 The Specimens construction

Four scale-down models have been adopted in the experimental work. In the first model, a single steel beam has been constructed as shown inFigure 8.This beam was constructed to investigate the steel beam strength without lateral constraints.

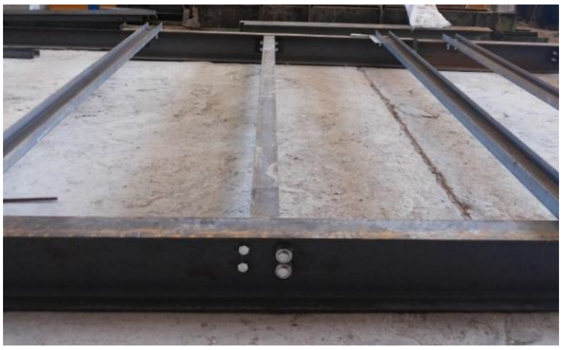

Figure 8 : Steel beam model**.**

In the second and third experimental models, concrete slab has been casted againstrough and smooth top flanges respectively were wooden deck has been used as shown in Figure 9 and Figure 10. Degree of lateral constraints which will caused by the concrete slab has been investigated in addition to whole system strength.

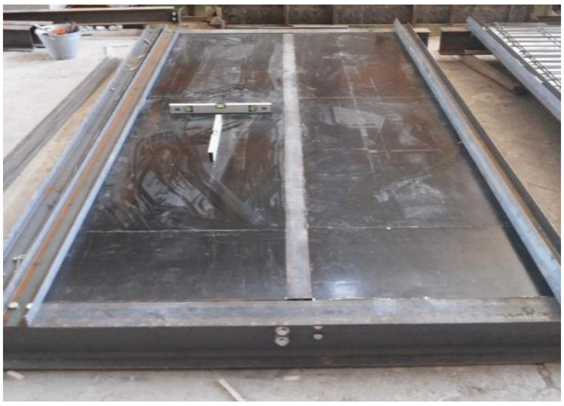

Figure 9 : Construction of the steel beam with concrete slab

Figure 10 : Steel beam with concrete slab and wooden deck after greasing top flange

Where in the third model the friction force between the concrete slab and the steel beam were reduced by greasing the top flange furthermore it was covered by isolated layer. Finally, in the fourth experiential model, concrete slab has been cast against a corrugated metal plate that in turn has been supported on top flange of the beam as shown in Figure 11.

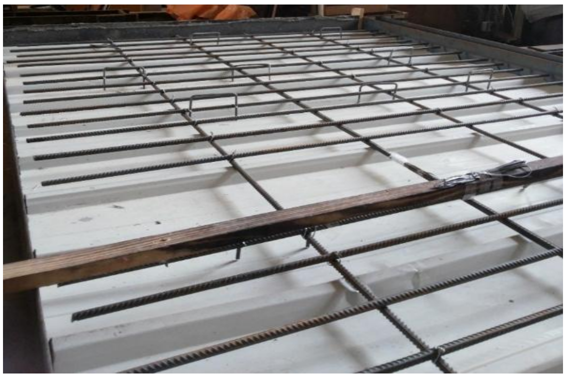

Figure 11 : Steel beam with concrete slab and metal deck construction

3.2 The specimens Property

3.2.1 Steel frame

Characteristics for steel sections adopted in this study have been presented with referring to Figure 12**and** Table 1below.

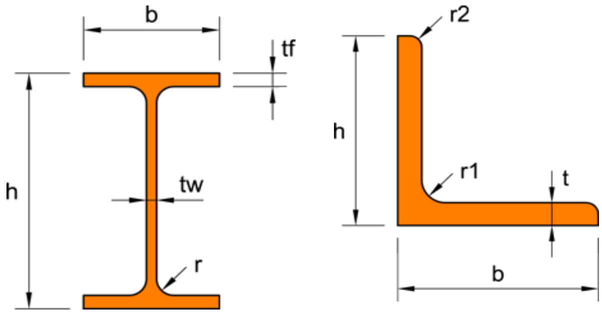

Figure 12: Reference dimensions for the adopted steel section

Table 1: Steel Parts details in millimeters**.**

Part	h	b	t_f	t_w	Length
Main Beam, IPE140	142	75	8	6	2900
Girder, IPE220	200	99	8	5.5	2000
Angle	100	100	5		100
Bolts diameter	16				

Figure 13 : Beam-Girder connection

From coupon test, the measured yield tensile strength for the steel beam was 309MPa, and the modulus of elasticity was 200,000MPa.

3.2.2 Reinforced Concrete Slab

The adopted concrete slab has following characteristics

1. Thickness and width are $t = 75\ mm$ $w = 1500mm$ respectively
2. The concrete slabs were reinforced by steel rebars as indicated below:
   - long direction: $\emptyset 10@300$ mm top and bottom
   - short direction: $\emptyset 10@300$ mm bottom
   - short direction: $\emptyset 10@100$ mm top

From concrete cubes test, the measured compressive strength of the concrete slab was 34 MPa. and the steel rebar tensile yielding stress was 415MPa.

3.3 Tests Setup

The specimens were examined by applying a uniform distributed load, the specimens with a total length of 2.9 m was set up on testing machine, two steel rods were supporting the specimens at each corner, the load were then applied by the hydraulic jack.

The hydraulic jack applies the load to the steel beams which will distribute the load to the sand bags were it was furnished above concrete slab.

The test setup is shown in test lab in Figure 14.

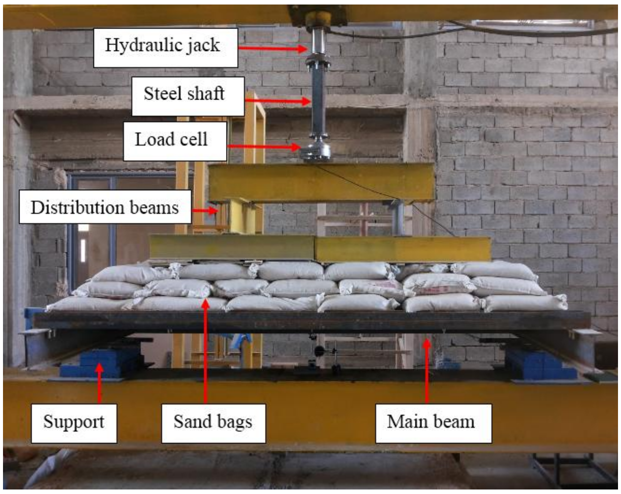

Figure 14 : Test setup.

3.4 Deformation measurement

The in-plane deflection and lateral displacement of the tested beams were measured using two dial gauges as shown in Figure 15. the dial gauges were placed at the mid span to record the lateral and vertical movements of the beam.

Figure 15 : Dial gauges installation

4. Experimental Tests Results

The general failure mode was inelastic lateral torsional buckling for the single steel beam. For the other models the test results showed that the concrete slab will prevent the lateral torsional buckling. The three remaining models were failed by flexure at ultimate loads as shown in
Table 2.

The lateral torsional buckling changes the deformation from predominantly in-plane bending to combined lateral deflection and twisting. The final failure pattern involves lateral deflection and twisting in combination with various extents of yielding and flange and/or web local buckling depending on the specific member characteristics [1].

When the concrete slab is supported by the steel beam, the beam upper flange is in compression, and restrained at all points. The twist of thatbeam will be counteracted by the concrete slab. Therefore, the concrete slab will prevent the steel beam form twisting due to the massive pressure subjected to the beam top flange as shown in Figure 16.

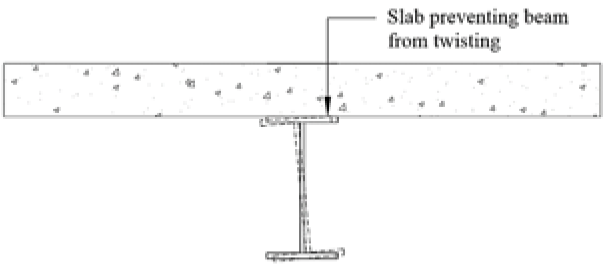

Figure 16 : Slab restraining the top flange from twisting.

Table 2 : Failure loads

Model type	Experimental Tests (Total load kN)	Analytical Evaluation forFull composite (Total load kN)	Analytical Evaluation Non-composite (Total load kN)
Single steel beam	71.87	72.94	
Steel-concrete beam with Rough	124.78	150	76.4

top flange			
Steel-concrete beam with Smooth top flange	109.04	150	76.4
Steel-concrete beam with Corrugated metal deck	119.78	131	72.69

A yielding stress of $F_y = 216\ MPa$ were adopted in the analyticalevaluation where the yield stress has been reduced by 30% to account for the effect of residual stress [2].

The load versus in-plane vertical deflection and out-plane lateral deflection curves, are shown in Figure 17,

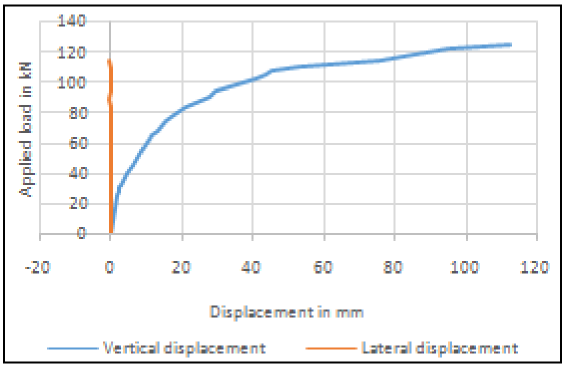

Figure 18, Figure 19 and Figure 20.

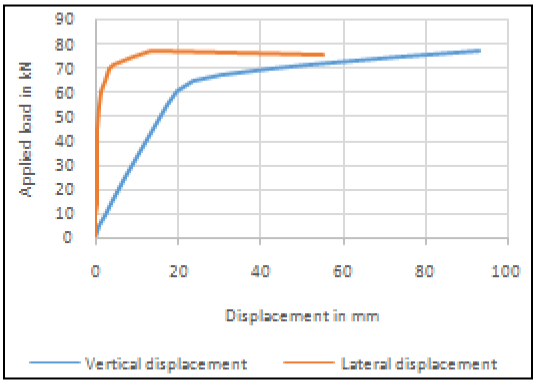

Figure 17 : Single Steel beam load-displacement curves

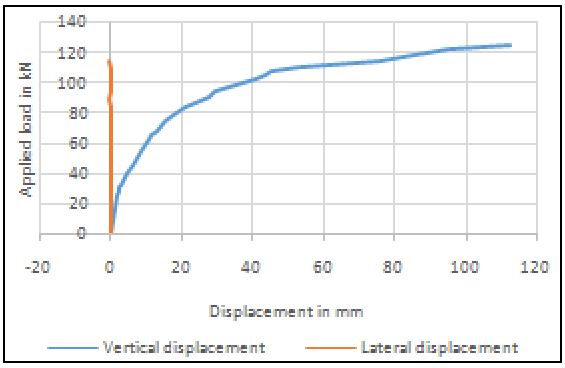

Figure 18 : Steel-Concrete Beam (rough flange) load-displacement curves

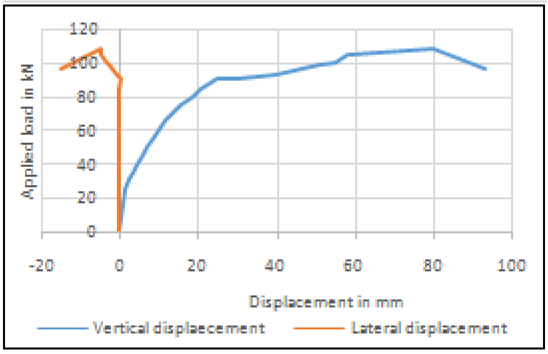

Figure 19 : Steel-Concrete Beam (smooth flange) load-displacement curves.

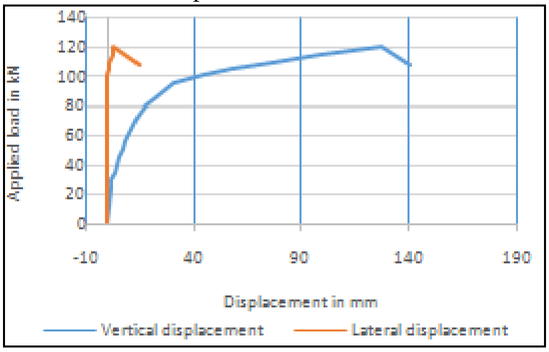

Figure 20 : Steel-Concrete Beam with corrugated metal deck load-displacement curves

The lateral displacement appeared in Figure 19 and Figure 20, was caused by local deformation as shown in Figure 29. The failure mode shapes for all models are presented in the figures below.

Figure 21 : Single steel beam after failure.

Figure 22 : Single steel beam after failure.

Figure 23 : Steel-Concrete Beam (rough flange) .

Figure 24 : Steel-Concrete Beam (rough flange) after failure.

Figure 25: Steel-Concrete Beam (smooth flange) after failure**.**

Figure 26: Steel-Concrete Beam (smooth flange) after failure.

Figure 27: Steel-Concrete Beam with corrugated metal deck after failure.

Figure 28: Steel-Concrete Beam with corrugated metal deck after failure.

Figure 29 : Top flange for consrete-steel beam after failure.

5. Conclusions

This study indicates that friction between slab and top flange of the beam, pressures acting on top flange, and lateral stiffness of slab all of them are adequate to restrain floor beams against lateral torsional buckling.

In all of experimental models, it has been noted that, the residual stresses have significant effect of beams behavior.This effect has been used to approximate the difference between the experimental works and the analyticalevaluation.
The actual strength of the steel-concrete beam without using shear connectors, was between the full composite action and non-composite action, i.e. partial-composite action is appeared due to the effectiveness of friction force which will make the beam behave as composite before the slip is occur.

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