NONLINEAR ANALYSES OF PARTIALLY COMPOSITE STEEL BEAMS ENCASED IN CONCRETE WITH INNOVATIVE POSITION OF STUD BOLTS

Raad K. Shukur
Asst. Profesor /Civil Eng. Dept.
College of Eng. / University of Baghdad.

ABSTRACT:

Static behavior of three partially encased composite steel beams with cambering under flexural condition is investigated in the context of studying some alternative positions for the headed studs. Shear resistance between the cambered I-shaped beam and the concrete was provided by headed studs in two positions: vertically welded on the bottom flange and horizontally welded on the faces of the web. In the present study, a nonlinear three-dimensional finite element analysis has been used to predict the load-deflection and moment-rotation behaviors of composite encased beams consisting of steel sections using the finite element computer program (**ANSYS V. 10**). Composite encased beams are analyzed and a comparison is made with available experimental load-deflection curves, good agreement with the experimental results is observed. Cambering of steel section is introduced on the steel section of the composite beams encased in concrete. It is found that using of steel section with cambering can increase the ultimate load capacity of the composite encased beam by relatively (15%) and also it is found that deflection are nearly (65% to 80%) the deflection of the same beam without cambering. Parametric studies have been carried out to study the increasing of the moment-carrying capacity due to the use of encased concrete; meanwhile the slip along the beams length is studied. The strain distributions along the steel section and encased concrete depth are also examined. The effects of concrete compressive strength on the stiffness of the composite encased beams are also investigated with the Poisson's ratio of concrete and the effect of cambering of steel-section.

KEYWORDS
Nonlinear Analysis, Composite beam, Flexural behavior, Cambering .

الخلاصة:

في البحث الحالي, تم التحري حول سلوك ثلاث نماذج من العتبات المركبة المثنية و المغلفة جزئياُ بالخرسانة تحت تأثير الاحمال الساكنة ضمن نهج عام يتمحور حول دراسة الموقع الافضل لوضع روابط القص (Shear Studs). تم توليد مقاومة القص بين الكونكريت و المقطع الفولاذي المثني و من خلال روابط القص عن طريق موضعين رئيسين: الروابط الملحومه طولياُ و الروابط الملحومه أفقياُ. أستخدم في الدراسة الحالية, طريقة العناصر المحددة للتحليل اللاخطي ثلاثي الابعاد

و ذلك لغرض تحري علاقة كل من الحمل بالهطول و كذلك العزم بالدوران للعتبات المركبة و التي تحتوي على عنصر فولاذي مثني مغلف بالخرسانة وباستخدام برنامج العناصر المحددة للتحليل الانشائي الـ(**ANSYS**). تم تحليل العتبات المركبة ذوات المقاطع المغلفة و تمت مقارنة نتائج منحنيات القوة و الهطول مع النتائج العملية المتوفرة, تم ملاحظة توافق جيد بين النتائج المستحصلة من البرنامج و النتائج العملية. تم توليد تحديب (أنثناء) في المقطع الفولاذي للعتبات المركبة المغلفة بالخرسانة. لقد لوحظ بأن استخدام المقاطع المثنية في العتبات المركبة و المغلفة بالخرسانة يؤدي الى زيادة قابلية تحمل تلك العتبات بمقدار (١٥٪), و كذلك لوحظ بأن الهطول الدوران يتراوح مابين (٦٥٪ الى ٨٠٪) من هطول الدوران للعتبات التي تحتوي على مقاطع مثنية. تم دراسة تأثير وجود الخرسانة المغلفة على زيادة قابلية تحمل العزوم للعتبات القشرية المركبة و المغلفة جزئياً بالخرسانة, في تلك الاثناء تم دراسة التزحلق الذي يحدث في سطح الاتصال و على طول العتب للعتبات المركبة أيضاً. بالاظافة الى ذلك تم دراسة نمطية توزيع الانفعالات على العمق الكامل للمقاطع الفولاذية و كذلك الخرسانة المغلفة. تم التحري عن مدى تاثير مقاومة أنضغاط الخرسانة على جسائة العتيات المركبة و المغلفة بالخرسانة.. و اخيراً, تم التحقق من تاثير كل من (Poisson's ratio), مقدار تحدب (ثني) المقطع الفولاذي و مقدار نعومة (دقة) النموذج المعمول بالـ(**ANSYS**) على قابليات تحمل العتبات المركبة.

INTRODUCTION:

Steel–concrete composite structures have been used more frequently in modern constructions, especially in multi-storey buildings. These materials combine the strength of steel with the compressive strength and the stiffness of concrete, producing a highly economical and interesting structural system. From the beginning, the most common type of composite beam in use has been an I-steel profile connected to the concrete slab or profiled steel-concrete composite slab. Given its importance, this traditional composite beam (Fig. 1(a)) has already been incorporated by design code procedures [1–3]. The composite action between the concrete and steel profile can be achieved by means of mechanical shear connectors as headed studs, proving to be an efficient shear connector. However, in several situations, it can be interesting to reduce the overall depth of the floor using the beams contained within the depth of the floor (Fig. 1(b)). The concrete between the flanges of the beam results in several advantages, such as high fire-resistance and load capacity, as well as a significant increase in the bending stiffness compared to a steel beam. The local buckling strength also increases in relation to the steel section, and the overall height of both composite beam and composite floor is reduced. In addition, lower construction cost compared to reinforced concrete (RC) or steel frame system and shorter construction time compared to RC can be obtained using encased beams. Therefore, the concrete cast in the flanges of the steel beam is an innovative and interesting alternative that needs to be investigated in details, as each detail of the components can modify the behavior of the encased beam. Despite the advantages in terms of structural behavior and costs, the encased beam is a constructive solution not totally understood yet, especially in relation to the headed studs contribution to load capacity and composite behavior. Currently, only the details shown in (Fig. 1(a) and (e)) are included in standard codes [1–3]. Comparing traditional composite beams (Fig. 1(a)) and partially encased beams (Fig. 1(e)), we note that the reinforced concrete between flanges increases the bending stiffness and reduces the vertical displacements. Among the innovative solutions shown in (Fig. 1), the focus here is on the contribution of the headed studs for the composite action.

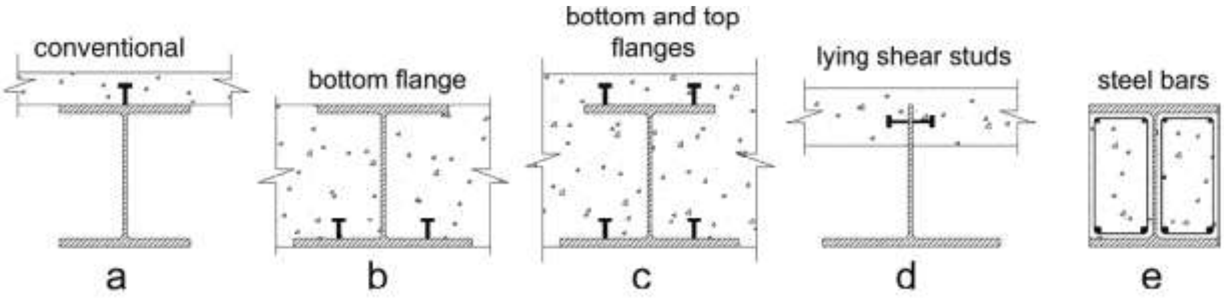


Fig. 1. Examples of composite beams.

*** PRECAMBERED STEEL BEAM:**

This type of steel composite beam is maximizing the structural advantage of both steel frame and reinforced concrete; it is produced by cambering the steel beam upwards over the span using suitable propping or jacking systems. Preflex beams have been used successfully in a number of road bridges as well as building structures. The typical construction sequence of a precambered beam is as follows [4], see (Fig. 2):

a. In the plant, setup a steel I-girder with a precamber supported at each end.
b. Prebend the steel girder by applying two concentrated loads at one-third of the span from both sides.
c. Cast the first phase of concrete at the level of the bottom flange of the steel girder while keeping in place the loads of the prebending phase of the girder.
d. Two days after casting the concrete, remove the prebending loads. As a result, the beam goes up, the precamber becomes smaller than the original precamber and the concrete is now subjected to compression.
e. Cast the second phase concrete on site [4].

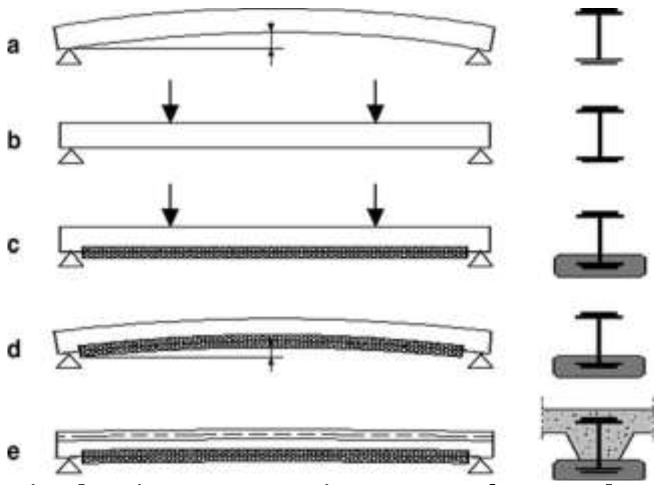


Fig. 2. Schematic Showing Construction Stages of precambered Beam [4].

STEEL-CONCRETE COMPOSITE BEHAVIOR IN ENCASED BEAMS:

Shear connectors are necessary when the natural bond is inefficient to achieve the desired steel-concrete interaction. Among the several types of available shear connectors used to provide composite action, the headed shear stud is the most common. In addition, headed shear studs are widely used welded on the upper flange of the steel profile in the vertical position. However, some new and interesting positions have been suggested. For example, studs vertically welded on the bottom flange or on both flanges [5], or horizontally on the web [6], see (Fig. 1(a), (b) and (d)). Many studies have been conducted for composite beams with headed shear studs welded in vertical position. However, very little experimental data is available for the case of headed studs horizontally welded on the web of the steel beam to achieve the composite action between steel and concrete. **Breuninger** [6] proposed an innovative composite cross section where the top flange of the steel beam is eliminated and the headed studs are directly welded to the web in the horizontal position, see (Fig. 1(d)). The headed studs in the horizontal position are called lying studs and experimental results showed that the load capacity is limited by: splitting of the concrete slab, splitting of the concrete slab, and tear-off or pull-out of the studs. The splitting failure of the lying studs is the most important failure mode; however, the design rules in standard codes are based on test results for only conventional studs and do not cover this failure type. Parameters such as concrete strength, thickness of concrete slab, distance, diameter and length of the studs, number and diameter of the stirrups, and reinforcement of slabs showed to be very important [6]. Among these parameters, the reinforcement of slab and the stirrups are the most important, mainly regarding the intersection between reinforcement and stirrups. Despite that the contribution of the headed studs to the composite action is unquestionable; **Dipaola et al.** [7] suggest the shear transfer mechanisms may be only provided by the adhesion and friction resistances of the steel-concrete interface (Fig. 3(a)). In the absence of bending moment, the area of the steel web is the shear resistant section, and for bending moment, the transference of shear forces is attributed to adhesion and friction resistant mechanisms [7]. When the upper flange of the steel beam is removed and lying studs are welded on the web, the shear strength of the beam decreases due to the small distance from the studs to the surface of the reinforced concrete slab (Fig. 3(b)). Using strut-and-tie models, **Kuhlmann and Kürschner** [8] showed the mechanism of shear transfer is a result of the load transferred by the studs and by the friction, but the latter is the most dominant mechanism. The contribution of the friction to the horizontal shear load capacity is only due to the web area and the horizontal studs. On the other hand, the vertical shear capacity depends on the web, concrete and stirrups. An interesting slim floor system is proposed by **Ju and Kim** [9] to minimize storey height and consists of inverted T-section steel beam and precast concrete rested on the bottom flange. Stirrups and lying studs on the top web are used to provide the composite action (Fig. 3(c)). In other research, where reinforcing bars and headed shear studs were combined to provide the composite action, the longitudinal shear force transfer occurred mainly by friction forces acting at the interface among the concrete encasement and the structural steel [9]. Additionally, pull-out test results of **Hegger and Goralski** [10] showed the load carrying capacity is higher for larger profiles due to the larger contact surface between the flange and the concrete encasement and also by the lower shortening of the concrete due to the shrinkage (Fig. 3(d)). The confinement effect of the steel profile in some areas of the concrete also increases the load carrying capacity. Regarding the failure modes, the absence of the reinforcement or headed studs leads to a failure without diagonal cracks. With reinforcing bars, the behavior becomes more ductile, and with headed studs, the failure is achieved by splitting the concrete around the studs [10].

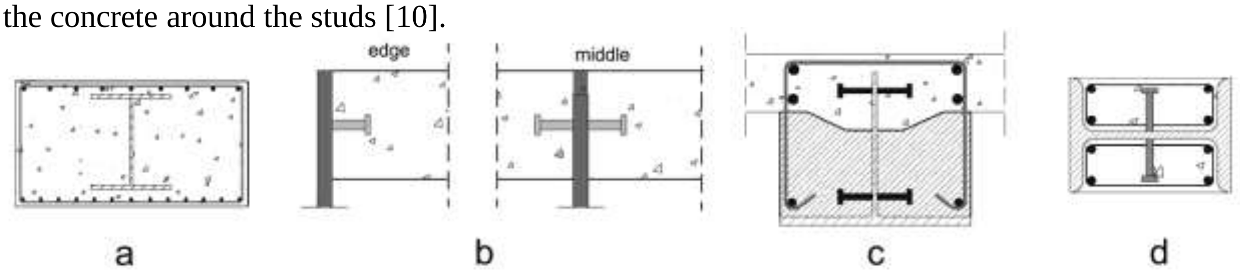


Fig. 3. Arrangement of headed shear studs;
(a) without headed studs [6]; (b) horizontally welded on the web [7]; (c) steel profile without top flange and (d) reinforcing bars and headed studs [10].

*** AVAILABLE EXPERIMENTAL RESEARCH**:

Works on encased composite beams dates back to the beginning of the last century, a series of testes have been conducted on this type of composite beam to study the influence of the concrete encasement on the behavior of steel beam section under different loading conditions. In the present study, **De Nardin and Lucia H.C., in (2008) [11]**, tested specimens (PEB-B, PEB-W and PEB) are chosen to verify the applicability of **ANSYS** computer program to analyze the encased composite beams and also to investigate the main parameters that affected it's the behavior.

- DETAILS OF THE TEST SPECIMENS:

A total of three simply supported (full-scale) composite partially encased beams with an asymmetrical structural (built-in) steel section and concrete filling were tested under two concentrated load, one of them being a beam without shear studs (specimen PEB) as a reference, and the remaining two beams are with studs, vertically welded on the top of the bottom flange, specimen (PEB-B), and horizontally welded on two opposite sides of the steel web, specimen (PEB-W). Five headed studs of (19 mm) diameter and total post-weld height (75 mm) were directly welded on each side of the web or bottom flange of the steel section, the centre-to-centre spacing of the studs was kept constant and equal to (480 mm). As the main parameter to be investigated was the shear stud position, all the three specimens of asymmetric steel beam were designed with exactly the same geometry. No longitudinal or transverse reinforcements were used in the specimens. The cross-sections and loading arrangement for the tested specimens are shown in (Fig. 4); the dimensions of steel sections, gross-sections and failure mode are given in (Table 1). The material properties are given in (Table 2).

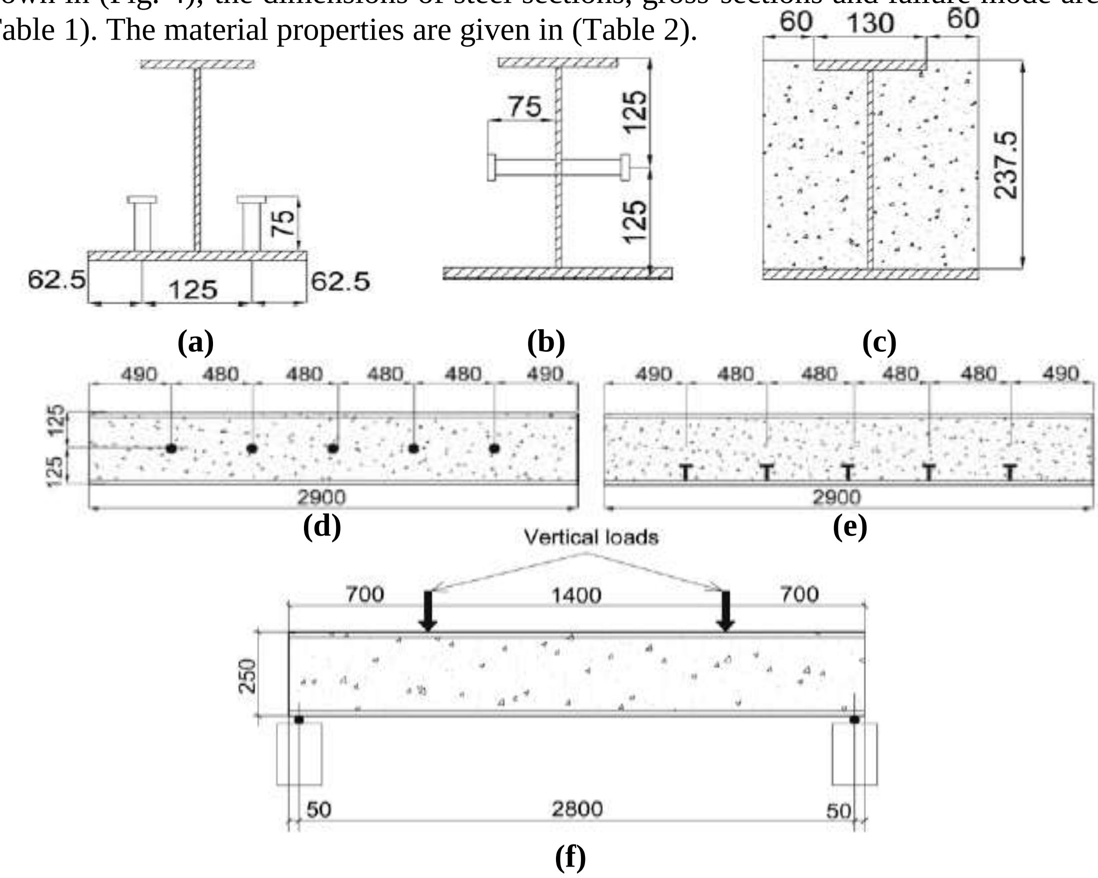


Fig. 4. Geometry of the Partially Encased Tested Specimens [11]:
(a) PEB-B Specimen Cross-Section, (b) PEB-W Specimen Cross-Section,

(c) Typical Cross-Section, (d) PEB-W: Studs on the Web, (e) PEB-B: Studs on the Bottom Flange, (f) Loading Arrangement, (All dimensions in mm).

Table 1: Descriptions, Dimensions of Steel Sections and Dimensions of Gross-Sections of the Tested Specimens.

Analyzed (Tested) specimen	Steel shape (ds×bf×tw×tf) (mm)	Cross-Section Dimensions(mm)
PEB	….	(250X250)
PEB-B	{250X(U=130, B=250)X6.3X12.5}	(250X250)
PEB-W	{250X(U=130, B=250)X6.3X12.5}	(250X250)

Table 2: Material Properties of the Analyzed (Tested) Specimens.

Analyzed (Tested) specimen	PEB	PEB-B	PEB-W
Concrete			
Compressive strength-(f'c)-(N/mm2)(♦)	46.540	46.540	46.540
Tensile strength-(fcr)-(N/mm2)(♥)	4.240	4.240	4.240
Young modulus- (Ec)-(N/mm2) (♣)	32288.6	32288.6	32288.6
Poisson's ratio-(ν)(♠)	0.2	0.2	0.2
Steel section			
Yield stress of steel-(fy)-(N/mm2)(♦)	….	308	308
Ultimate stress of steel-(fy)-(N/mm2)(♦)	….	469	469
Young modulus- (Es)-(N/mm2) (♠)	….	200000	200000
Poisson's ratio-(ν)(♠)	….	0.3	0.3
Shear connector (studs)	….	D19 mm	D19 mm
Yield stress of steel-(fy)-(N/mm2)(♠)	….	500	500
Young modulus- (Es)-(N/mm2)(♠)	….	200000	200000
Poisson's ratio-(ν)(♠)	….	0.3	0.3
Notation			
Symbol	Description		
(♣)	Equation (1)		
(♠)	Assumed		
(♥)	Equation (2)		
(♦)	From test		

- $E_c = 4733\sqrt{f'_c}$ ……………………………………………………………………………. (1)

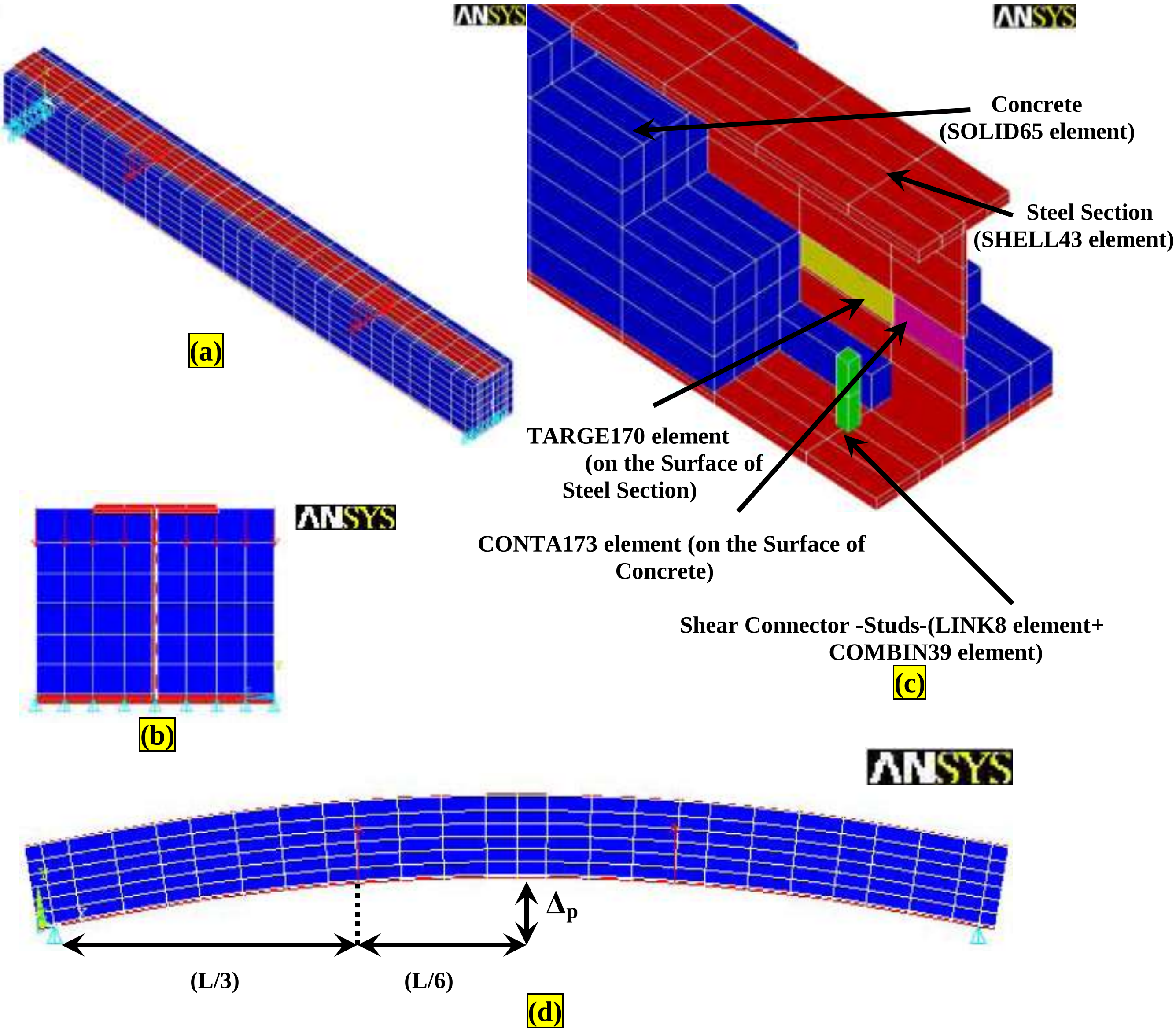
- $f_{cr} = 0.622\sqrt{f'_c}$ ……………………………………………………………………….. (2)

Where:
E_c = Modulus of elasticity of concrete in (MPa).
f'_c= Cylinder uniaxial compressive strength (MPa).
f_{cr}= tensile strength of concrete (MPa).

*** FINITE ELEMENT MODEL:**

- SOFTWARE, ELEMENT TYPES AND MESH CONSTRUCTION:

Advances in computational features and software have brought the finite element method within reach of both academic research and engineers in practice by means of general-purpose nonlinear finite element analysis packages, with one of the most used nowadays being **ANSYS**. The program offers a wide range of options regarding element types, material behaviors and numerical solution controls, as well as graphic user interfaces (known as GUIs), auto-meshers, and sophisticated postprocessors and graphics to speed the analyses. In the present study, the structural system modeling is based on the use of this commercial software. The finite element types considered in the model are as follows: elastic-plastic shell **(SHELL43)** and solid **(SOLID65)** elements for the steel section and the concrete slab, respectively, and nonlinear springs **(COMBIN39)** to represent the shear connectors. Both longitudinal and transverse reinforcing bars are modeled as discrete using **(LINK8)** element. Rigid-to-flexible contact mechanisms are used to model the interface contact surface between the structural steel section and the encased concrete. The rigid target surface (encased steel section which is represented by **(SHELL43)** element) modeled with **(TARGE170)** elements, while the contact flexible surface (concrete encasement which is represented by **(SOLID65)** elements) modeled with **(CONTA173)** elements. The element **(SHELL43)** is defined by four nodes having six degrees of freedom at each node. The deformation shapes are linear in both in-plane directions. The element allows for plasticity, creep, stress stiffening, large deflections, and large strain capabilities [12]. The element **(SOLID65)** is used for three dimensional modeling of solids with or without reinforcing bars (rebars capability). The element has eight nodes and three degrees of freedom (translations) at each node. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep [12]. The rebars **(LINK8)** element are capable of sustaining tension and compression forces, but not shear, being also capable of plastic deformation and creep and have two nodes with three translation degrees of freedom at each node. The element **(COMBIN39)** is defined by two node points and a generalized force–deflection curve and has longitudinal or torsional capability. The longitudinal option is a uniaxial tension–compression element with up to three degrees of freedom (translations) at each node. Symmetry of the composite encased (straight and preflex) beams is taken into account by modeling a full scale beam span. A typical finite element mesh for a composite encased beam is shown in (Fig. 5).



<u>Fig. 5.</u> Finite Element Mesh for (PEB-B) Model:
(a) Isometric-View, (b) Front-View, (c) Internal Section, (d) Precambered Shape.

The following equations used to calculate the amount of forces required to produce the upward movement (cambering) of simply support steel section subjected into two forces at distance (L/3) from its two ends for a given allowable compressive stress in the steel beam [13].

Upward deflection $\Delta_p = \dfrac{23PL^3}{648EI}$ ……………………………..……......……...………... (3)

Bending moment $M = \dfrac{PL}{3}$ ……………..…………………………………….……………….. (4)

Compression flange stress $\sigma = \dfrac{My}{I}$ …………….…....………………………...………... (5)

By substituting in equation (6.3):

$$\Delta_p = \frac{23\sigma L^2}{216Ey} \quad \text{......} (6)$$

$$P = \frac{3\sigma I}{Ly} \quad \text{......} (7)$$

Where:

Δ_p in **(mm)**= cambering produced in the steel section.

P= force applied to the a steel section to produced cambering.

σ= Allowable compressive stress in the steel beam - (N/mm2).

L= Clear span of the tested specimens-(mm).

E=Es= (Young modulus of steel=200,000 N/mm2).

y= Distance from the steel section centroid to the top surface of compression flange in (mm).

- MATERIAL MODELING:

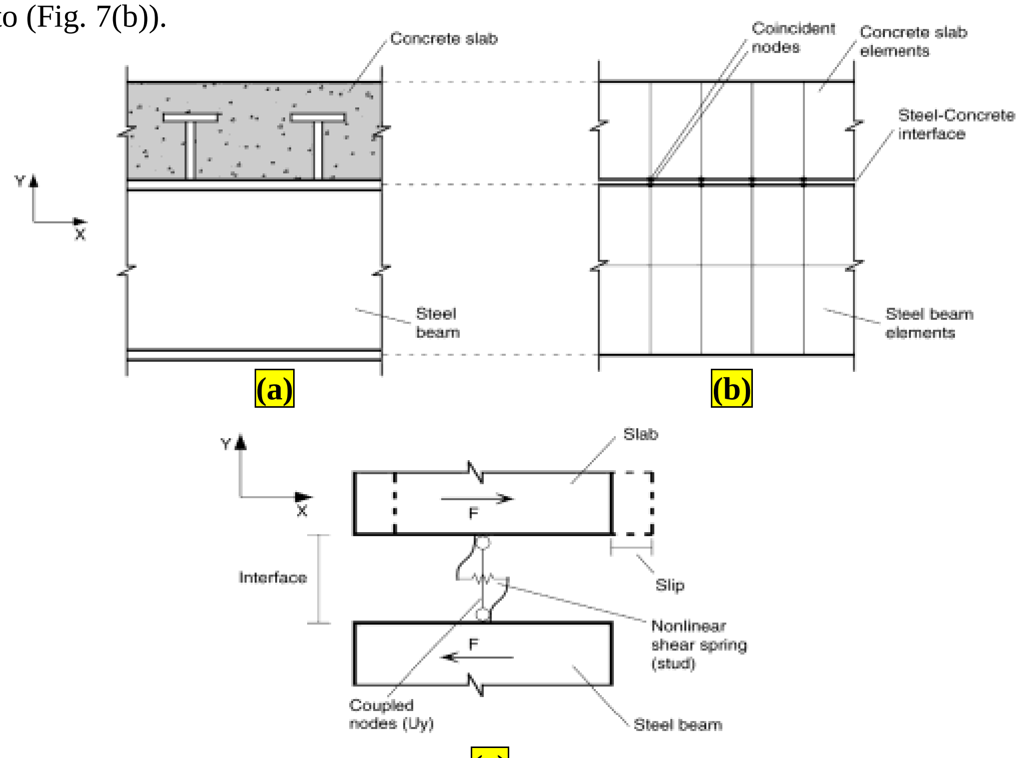
The von Mises yield criterion with isotropic hardening rule (multilinear work-hardening material) is used to represent the steel beam (flanges and web) behavior. The stress–strain relationship is linear elastic up to yielding, perfectly plastic between the elastic limit and the beginning of strain hardening. The von Mises yield criterion with isotropic hardening rule is also used for the reinforcing steel. An elastic-linear-work hardening material is considered, with tangent modulus being equal to (1/10000) of the elastic modulus, in order to avoid numerical problems. The values measured in the experimental tests for the material properties of the steel components (steel beam and reinforcing bars) are used in the finite element analyses. The concrete encasement behavior is modeled by a multilinear isotropic hardening relationship, using the von Mises yield criterion coupled with an isotropic work hardening assumption. The uniaxial behavior is described by a piece-wise linear total stress–total strain curve, starting at the origin, with positive stress and strain values, considering the concrete compressive strength (f'_c) corresponding to a compressive strain of (0.2%). The stress–strain curve also assumes a total increase of (0.05 N/mm2) in the compressive strength up to the concrete strain of (0.35%) to avoid numerical problems due to an unrestricted yielding flow. The concrete element shear transfer coefficients considered are: (0.25) for open crack and (0.8) for closed crack. Typical values range from (0 to 1), where (0) represents a smooth crack (complete loss of shear transfer) and (1) a rough crack (no loss of shear transfer). The default value of (0.6) is used as the stress relaxation coefficient (a device that helps accelerate convergence when cracking is imminent). The crushing capability of the concrete element is also disabled to improve convergence. The concrete encasement compressive strength is taken as the actual cylinder strength test value. The concrete tensile strength and the Poisson's ratio are assumed as (1/10) of its compressive strength and (0.2), respectively. The concrete elastic modulus is evaluated according to equation (1) mentioned above. The model allows for any pattern of stud distribution to be considered. In all analyses, the number/spacing of studs adopted in the experimental programmers is utilized. As far as the shear connector behavior is concerned, the load–slip curves for the studs are used (obtained from available push-out tests) by defining a table of force values and relative displacements (slip) as input data for the nonlinear springs. These springs are modeled at the steel–concrete interface [14], as shown in (Fig. 6). the behavior of the interface surface of contact between the steel section and concrete encasement is modeled according to the basic **Coulomb friction model**, in which, two contacting surfaces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to each other. This state is known as sticking. The **Coulomb friction model** defines an equivalent shear stress (τ), at which sliding on the surface begins as a fraction of the contact pressure (p) as [12]:

$\tau_{lim} = \mu p + COHE, \ |\tau| \leq \tau_{lim}$ .... (8)

where:

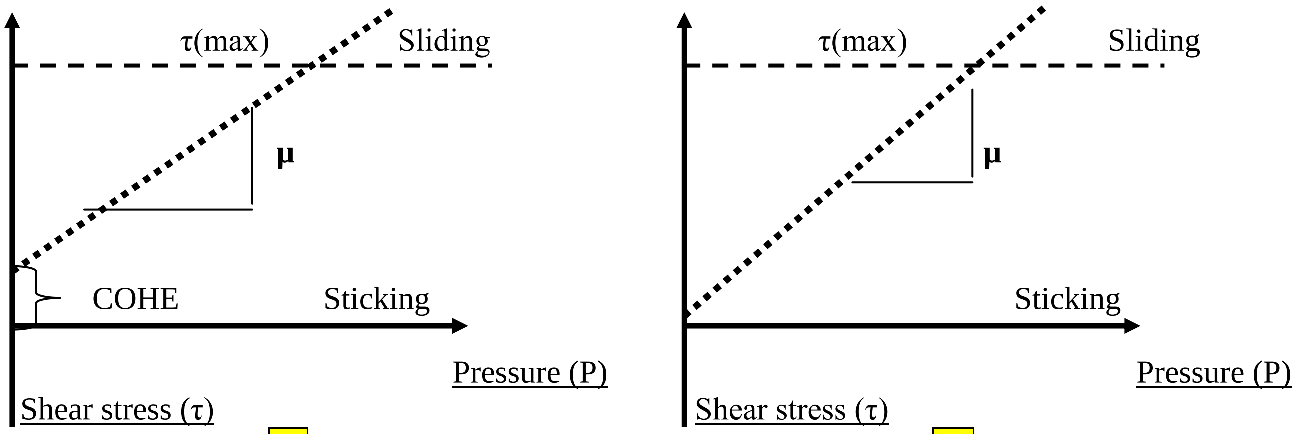
τ_{lim} = limit shear stress, τ= equivalent shear stress, μ= the friction coefficient, P= constant normal pressure, COHE= cohesion sliding resistance (stress unite).

Once the shear stress is exceeded, the two surfaces will slide relative to each other. This state is known as sliding. The sticking/sliding calculations determine when a point transitions from sticking to sliding, see (Fig. 7). **ANSYS** provides two models for Coulomb friction [12]: Isotropic friction (2-D and 3-D contact): which is based on a single coefficient of friction (MU) and the Orthotropic friction (3-D contact): which is based on two coefficients of friction (MU1 and MU2). In the present study, (3-D) Isotropic friction model is used with single coefficient of friction (MU), and the cohesion sliding resistance (COHE) set to (0.00) making (Fig. 7(a)) change to (Fig. 7(b)).



(a) (b) (c)

<u>Fig. 6.</u> Modelling of shear connectors (longitudinal view) [14]:
(a) Shear studs in a typical composite beam. (b) Shear studs in a typical composite beam finite elementmesh. (c) Representation of the shear stud model.



(a) (b)

Fig. 7. Frictional Models [12].

APPLICATION OF LOAD AND NUMERICAL CONTROL:

Regarding application of load, concentrated loads are incrementally applied to the model by means of an equivalent displacement to overcome convergence problems (displacement control). For the convergence criterion, the **L2-Norm** (square root sum of the squares) of displacements is considered. Concentrated loads are represented by means of point loads applied at nodes. These concentrated loads are also applied to the model incrementally using the load control strategy and the **L2-Norm**. The tolerance associated with this convergence criterion (**CNVTOL** command of **ANSYS**) and the load step increments are varied in order to solve potential numerical problems. Whenever the solution does not converge for the set of parameters considered, as far as load step size and converge criterion are concerned, the **RESTART** command is used in conjunction with the **CNVTOL** option. **ANSYS** allows two different types of restart: the single-frame restart and the multi-frame restart, which can be used for static or full transient structural analyses. The single-frame restart only allows the user to resume a job at the point it stopped. The multi-frame restart can resume a job at any point in the analysis for which information is saved. This capability enables multiple model analyses, presenting more options for data retrieval after an undesired aborted solution. The second approach is used throughout the present analyses. For the case in which only one point load is applied to the system, there is a direct relationship between force and displacement, making the displacement control method easier to be utilized. The load control method is, however, less efficient than the displacement control method in nonlinear analyses. This fact is observed especially when the applied load approaches the ultimate load of the system, as an incremental increase in the load leads to a significant increase in the corresponding displacements, causing difficulties in terms of numerical convergence. For the type and size of the finite element problem investigated, the load control method demanded, on average, (70%) more disk space and took (150%) longer to be processed than similar displacement control solutions. The finite element analysis of the models was set up to examine two main behaviors: (initial cracking of the composite encased beams and the strength limit state). The Full Newton-Raphson method of analysis is used to compute the nonlinear response. The application of the loads up to failure was done incrementally as required by the Newton-Raphson procedure.

*** ANALYSIS PROCESS FOR THE ANALYZED FINITE ELEMENT MODELS:**

- ANALYSIS OF THE STRAIGHT ENCASED COMPOSITE BEAMS:

The finite element analyses for the straight simply support composite encased beams under concentrated forces have been carried out using static analysis type. The solution controls command dictates the use of a linear or non-linear solution for the finite element model. The program behavior upon non-convergence for this analysis was set such that the program will terminate but not exit. The most important typical commands utilized in a nonlinear static analysis are shown in (Table 3). The rest of the commands were set to defaults.

Table 3: The Most Important Commands Used to Control Nonlinear Analysis.

Commands	Description
solution printout controls	all solution items such as {nodal DOF solution, nodal reaction loads, element solution (element nodal stresses+element elastic and plastic strains…etc),…etc}
print frequency	write every substep
controls for database and results file written.	all solution items such as {nodal DOF solution, nodal reaction loads, element solution (Element nodal stresses+element elastic and plastic strains…etc),…etc}
print frequency	write every substep
time at end of loadstep	(experimental failure load)X(1.1)
time Step size	(1%) from the time at end of loadstep
automatic time stepping	on
max no. of substeps	time Step size
min no. of substeps	(10%) from the max no. of substeps

At first trials for the analysis, the values for the convergence criteria (force and displacement) are set to defaults except for the tolerances. The tolerances for force and displacement are set as (15 times) the default values as shown in (Table 4), which represent the commands used for the nonlinear algorithm and convergence criteria. However, when the composite encased beams began cracking, convergence for the non-linear analysis was impossible with the default values. The displacements converged, but the forces did not. Therefore, the convergence criterion for force was dropped and the reference value for the Displacement criteria was changed to (5), this value is then multiplied by the tolerance value of (0.01) to produce a criterion of (0.05) during the nonlinear solution for convergence. A small criterion must be used to capture correct response.

Table 4: Nonlinear Algorithm and Convergence Criteria Parameters.

Commands	Description	
equilibrium iteration	100	
criteria to stop an analysis	stop and stay	
Set Convergence Criteria		
Label	F (force)	U (displacements)

reference value	calculated	calculated
convergence tolerance	0.001	0.010
Norm	L2 (SRSS value)	L2(SRSS value)
Minimum reference value	not applicable	not applicable

- ANALYSIS OF THE PRECAMBERED ENCASED COMPOSITE BEAMS:

Analyses for the precambered encased composite beams were similar to the analyses of the straight encased composite beams. However, different load steps were used. The first load step taken was to produce camber in the steel beam only in which the upward movement of the beam resulted, meanwhile all others element consisting the encased beams considered to be a **(DEAD ELEMENTS)** according to **ANSYS** options. **RESTART** command then used to re-analyze the beams due to its original state of loading **(Experimental Researches paper)**, during this, the flexural reinforcements, shear reinforcements, concrete and shear studs elements are re-activated and the two preflexing forces are neutralized by two forces having the same magnitude but opposite direction. The preflexing loads are removed. As a result, the beam goes down a little due to self weight (gravity-loads) and the stress recovery of the steel beam, the precamber amount becomes smaller than the original cambering, and the concrete is now subjected to compression. The load-deflection curves for analyzed composite partially encased beams {{(PEB-B+PEB-W) **De Nardin** and **Lucia H.C.,** (2008) [11]}} which were obtained numerically by the finite element method using **ANSYS (V.10)** computer program for straight and preflex steel section and compared with the experimental results are presented in (Fig. 8) through (Fig. 11); respectively. The goal of the comparison of the finite element models and the beams experimental works is to ensure that the elements types, meshing, material properties, real constants and convergence criteria are adequate to model the response of the beams.

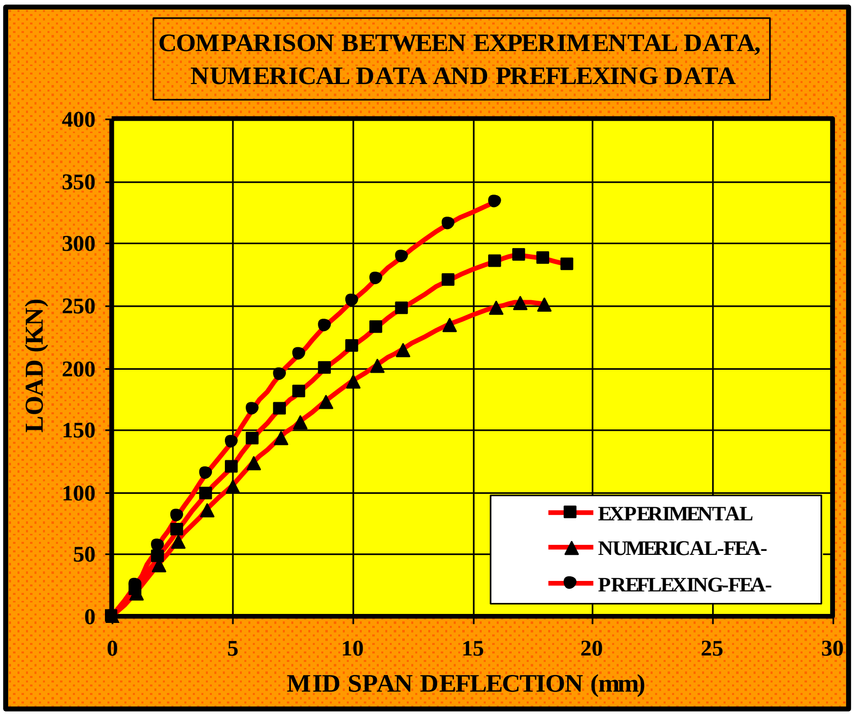
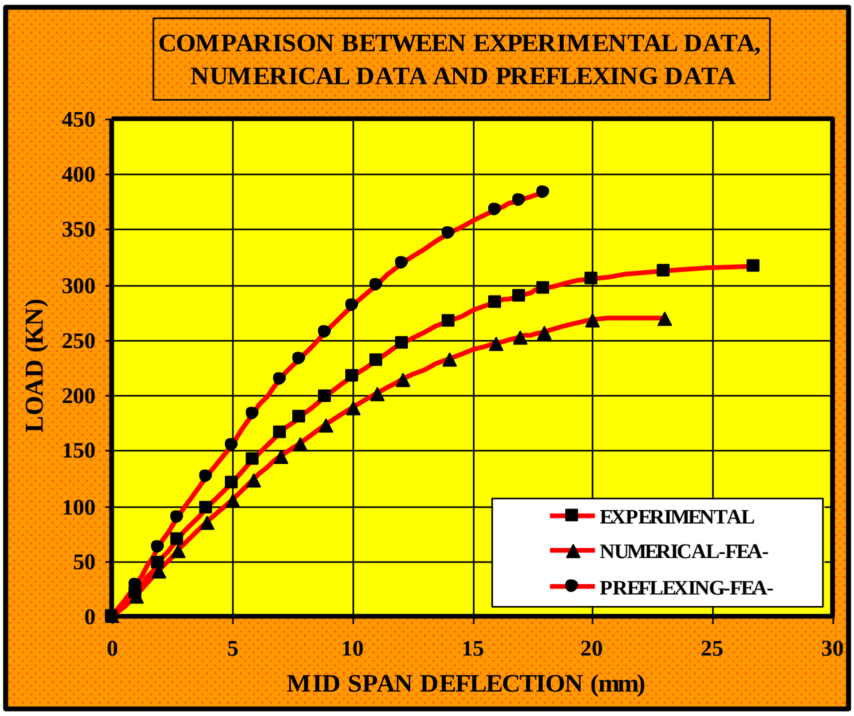
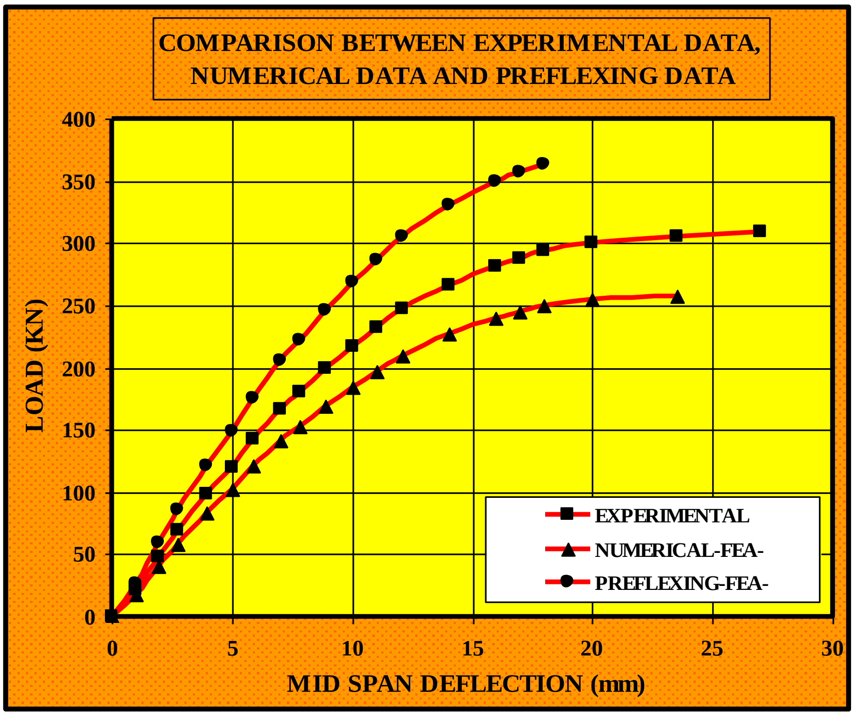


Fig. 8. Finite Element Analysis Result for Model (PEB).



<u>Fig. 9.</u> Finite Element Analysis Result for Model (PEB-B).



<u>Fig. 10.</u> Finite Element Analysis Result for Model (PEB-W).

BEHAVIOR AT ULTIMATE LOADS:

The analytical and experimental values of the ultimate loads for straight and preflex composite encased beams which presented in (Fig. 8) through (Fig. 10); respectively, are summarized in (Table 5). (Table 5) showed that The preflex load for the analyzed specimen (PEB-B) is higher than the preflex load of the analyzed specimen (PEB-W), this is due to the presence of vertical studs {specimen-(PEB-B)} which are more efficient than horizontal ones {specimen-(PEB-W)} in providing the composite action between the steel profile and the concrete encasement, because the vertical stresses from concrete encasement acting on the surface of bottom flange and also the friction forces developed in the same surface is tremendously higher than that developed in the surface of steel section web. The analyses finished (Done) for the partially encased composite analyzed specimens (PEB-B+PEB-W) due to the excessive cracking in the constant moment region.

Table 5: Comparison between Analytical and Experimental Values of the Ultimate Loads.

Tested specimen	Experimental (ultimate loads)	Analytical (ultimate loads)-straight beams	A%	Analytical (ultimate loads and)-preflex beams	B%
PEB	288	252	12.5	330	12.7
PEB-B	317	270	14.8	382.7	17.2
PEB-W	309	258	16.5	363.5	15.1
Notation					
Symbol	Description				
A%	$\frac{(P_u)_{exp} - (P_u)_{ANSYS\text{-}Straight}}{(P_u)_{exp}}$				
B%	$\frac{(P_u)_{ANSYS\text{-}Preflex} - (P_u)_{exp}}{(P_u)_{ANSYS\text{-}Preflex}}$				

BEHAVIOR AT MAXIMUM DEFLECTIONS:

The analytical and experimental values of the maximum deflections for straight and preflex composite encased beams are summarized in (Table 6). The load-deflection curves which presented in (Fig. 8) through (Fig. 11); respectively, for the analyzed specimens in which the corresponding experimental, theoretical and preflexing curves are superimposed, show that the curves are lie very close to each other at initial stages for all the specimens. However, there seems to be some deviation between the results near the failure. The discrepancy may be due to the inadequacy in concrete and interface behavior modeling. It was found that the deflections are nearly (85% to 95%) the deflections of the same experimental beam for straight beam situation, and (65% to 80%) of the same experimental beam for preflexed beam situation.

Table 6: Comparison between Analytical and Experimental Values of the Maximum Deflections.

Tested specimen	Experimental Deflections	Analytical (Deflections) straight beams	Analytical (Deflections) preflex beams
PEB	18.5	16	15
PEB-B	26.7	23	18
PEB-W	27.36	23.8	19

*** THE PARAMETRIC STUDY:**

A parametric study has been done on the same samples that have been analyzed. Many parameters can be studied in the analyzed models to examine the effect of each parameter on the behavior of the models results. Some models were chosen to study the effect of encased concrete in the increasing of moment-bearing capacity, meanwhile other are chosen to study the slip along the composite partially encased beams length. The strain distributions along the steel section and encased concrete depth are also examined. The Poisson's ratio of concrete and the effect of cambering of steel-section are also investigated.

- THE EVALUATION OF SLIPS ALONG THE COMPOSITE ENCASED BEAMS INTERFACE:

The partially encased beams (PEB), (PEB-B) and (PEB-W) which were described in (Fig. 4) and (Fig. 5) are chosen for the evaluation of the slip along the steel-encased concrete interface surface length under different loading magnitudes. The first part of the curves presented a stiff behavior corresponding to an initial bond provided by the concrete–steel connection. It is named "adhesion" or "chemical bond", and corresponds to a small part of the bond strength, which is active mainly in the early stages of loading, when the displacements are small. As shown in details in (Fig. 11), for Specimen (PEB), the adhesion broke when the load was approximately (10 kN). The rupture of the adhesion was not clearly identified for the specimens with mechanical connectors (PEB-B and PEB-W). In these specimens, it can also be seen that the presence of the mechanical connectors contributes to increasing the maximum load and slightly changes the applied load-slip relationship. Although all specimens behaved in a similar way in both pre-peak and post-peak branches, specimen (PEB) presented a slight reduction of the load capacity after the ultimate load had been reached. In the pre-peak branch, the specimens with mechanical connectors behaved in a stiffer manner and the specimen with vertical headed studs was stiffer than the specimen with horizontal studs. Therefore, the results indicated that the end slips of the specimens with studs were smaller than the specimen without studs and these mechanical shear connectors were more effective when the applied load was increased. Comparing the end slips in all specimens, the vertical position of the studs on the bottom flange was the most effective in all loading stages. It should be mentioned that the values of the slips were obtained from the (DOF solution, X-component of displacement).

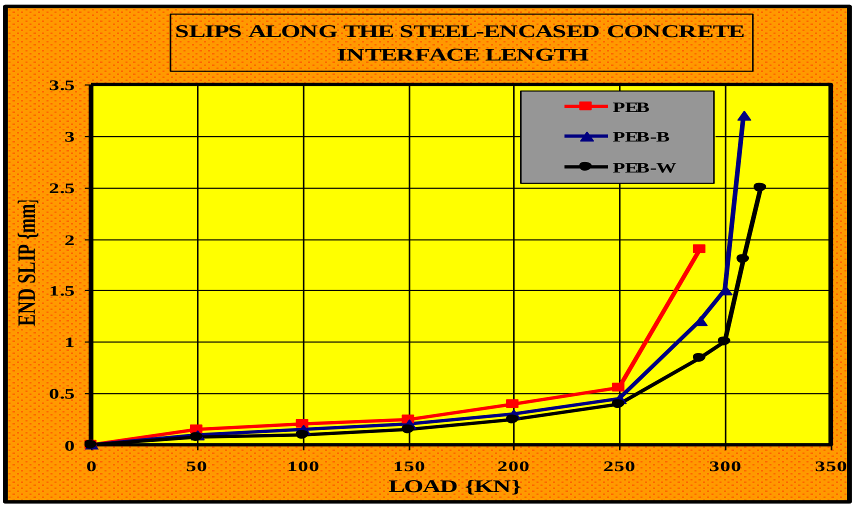


Fig. 11. Finite Element Results of Model (PEB, PEB-B and PEB-W) to Show the End Slips along the Steel-Encased Concrete Interface.

- THE EVALUATION OF STRAIN DISTRIBUTIONS ALONG THE STEEL SECTION AND ENCASED CONCRETE DEPTH:

The laminated encased beams (PEB), (PEB-B) and (PEB-W) which were described in (Fig. 5) are chosen to examine the strain distributions along the depth of both steel section and concrete encasement under different loading magnitudes as shown in (Fig. 12) through (Fig. 17). In the case of Specimen (PEB), without mechanical shear connectors, the strains of the steel profile increased with the same ratio until the ultimate state (when the applied load was equal to Fu)-(Fig. 12). Additionally, the strains on the bottom and top flanges presented approximately the same values. On the other hand, the strains of Specimen (PEB-B) presented an abrupt change in the tension zone, which did not occur in the compression zone and the increased proportionally to the neutral axis distance (Fig. 13). Additionally, the change of the strain behavior became more expressive when the applied load in each loading point reached (250 KN). The behavior of Specimen (PEB-W) was very similar to (PEB), including the values of the strains. Apparently, the horizontal studs were less effective than the vertical ones in providing the composite action and increasing the load carrying capacity (Fig. 14). By means of the neutral axis, the encasement concrete was more effective for Specimen (PEB-B), as such an axis was higher than in the other specimens.

- STRAINS IN THE BENDING AND SHEAR ZONES OF THE BEAM:

A SPECIMEN (PEB): WITHOUT SHEAR MECHANICAL CONNECTORS:

For the specimen without mechanical connectors (PEB), the strains increased proportionally to the neutral axis distance until (250 Kn) at a zone under constant shear. For the ultimate load (Fu), the strains in some points presented a sudden change (Fig. 15). Comparing the strain results for Specimen (PEB at (35 cm) of the end and mid-length, the sudden change could be only observed at the first zone, where the shear was constant. Probably, the natural bond at the interface between the steel profile and the concrete encasement was destroyed by the shear stress. Therefore, it can be said that the partially encased beam only behaved as a composite beam until the load of (250 KN). After that, the natural bond of the steel-concrete interface was broken, this was more evident in the length of the beam under shear constant. Regarding the strains at the mid-length of the beam, the natural bond was not broken in the constant moment zone, where the shear stresses are zero.

B SPECIMEN (PEB-B): WITH VERTICAL HEADED STUDS WELDED ON THE BOTTOM FLANGE:

The strains of Specimen (PEB-B) presented a large variation of the distribution in both moment and shear constant zones (Fig. 16). Apparently, the presence of vertical studs in the tensile zone modified the contribution of the natural bond and Specimen (PEB-B) did not behave as a composite beam from the first stages of loading. The sudden change of the strains was more expressive in the constant shear zone.

C SPECIMEN (PEB-W): WITH HORIZONTAL HEADED STUDS WELDED ON THE WEB:

The strains of the specimen with horizontal studs behaved as the specimen without mechanical shear connectors in the mid-length of the beam (Fig. 14). At (35 cm) of the beam end, abrupt changes could be observed from the first stages of loading, especially in the compressive zone (Fig. 17). These results showed that the headed studs horizontally welded on the web were not efficient regarding composite action.

Finally, all tested specimens showed a sudden change of the strains in the shear constant zone. Furthermore, the changes of strains occurred at the same points of the measurement but for different levels of the loading. Additionally, the change of the strains was first recorded in Specimen (PEB-W) and with a lower loading level.

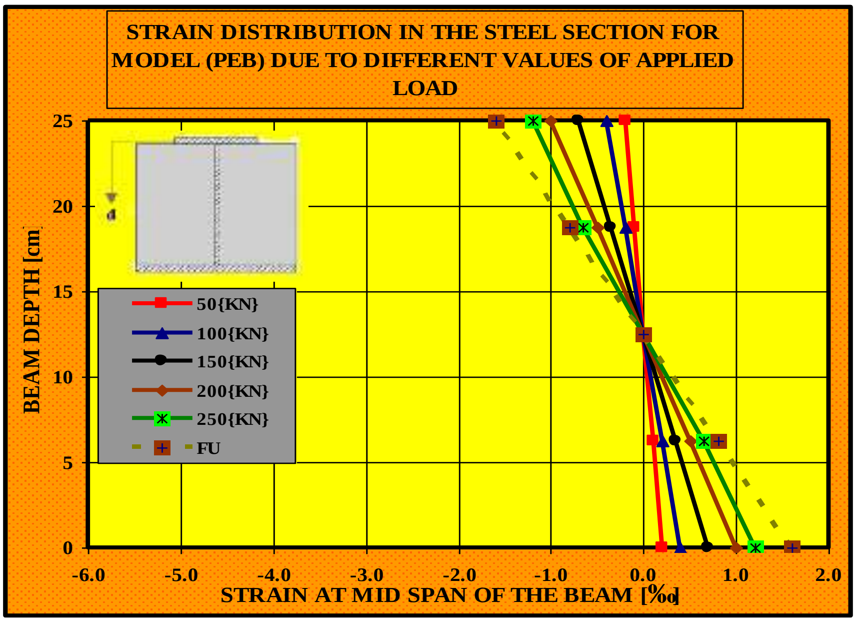


Fig. 12. **Strain Distribution along the Depth of Steel Section for Model (PEB).**

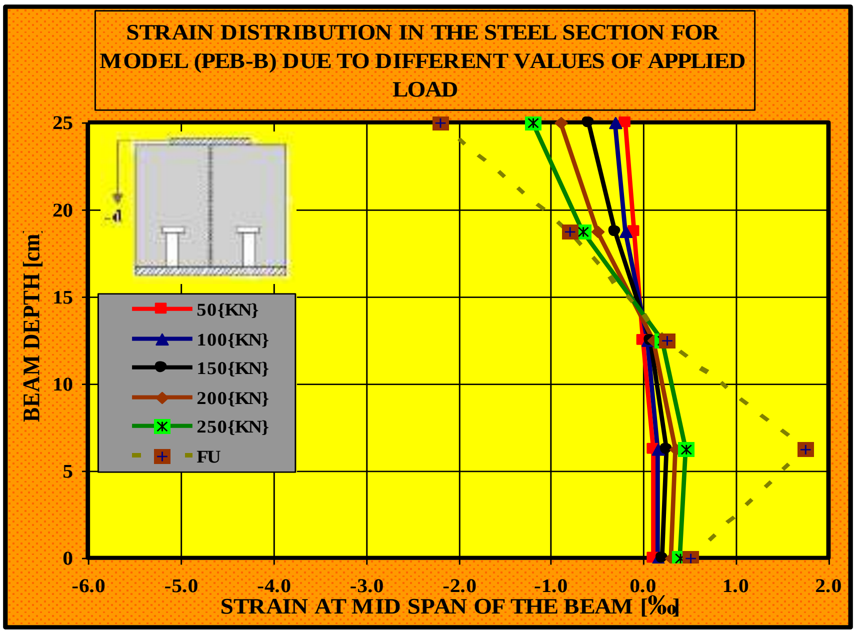


Fig. 13. **Strain Distribution along the Depth of Steel Section for Model (PEB-B).**

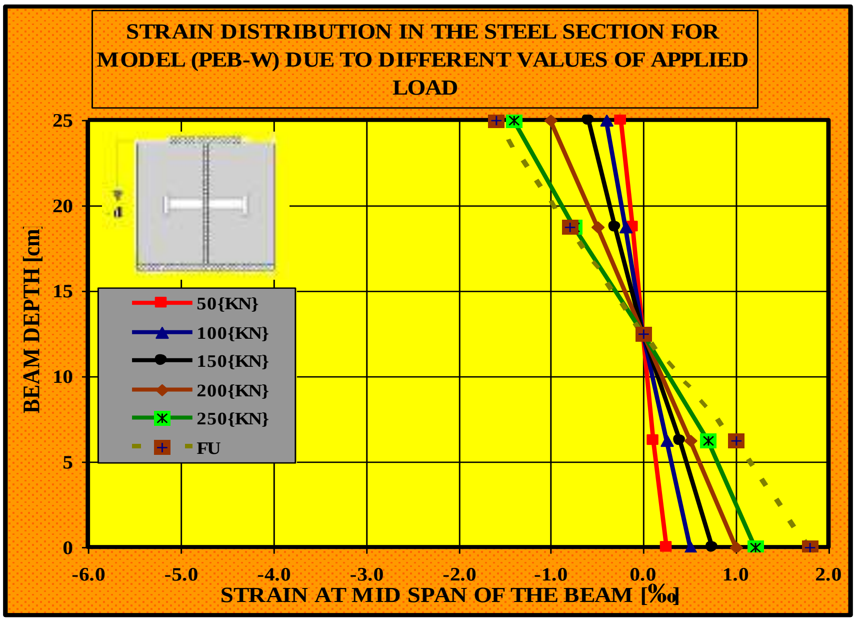


Fig. 14. **Strain Distribution along the Depth of Steel Section for Model (PEB-W).**

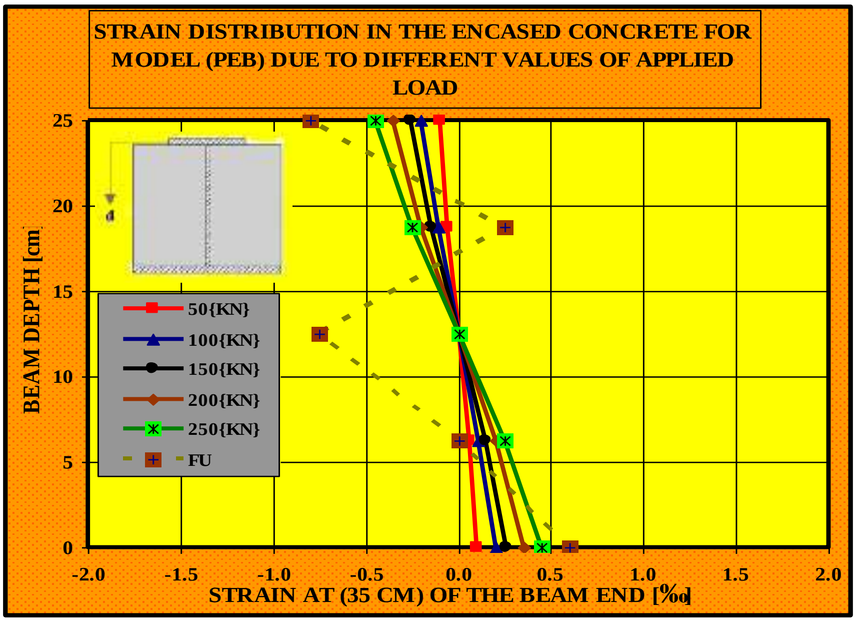


Fig. 15. **Strain Distribution along the Depth of Encased Concrete for Model (PEB).**

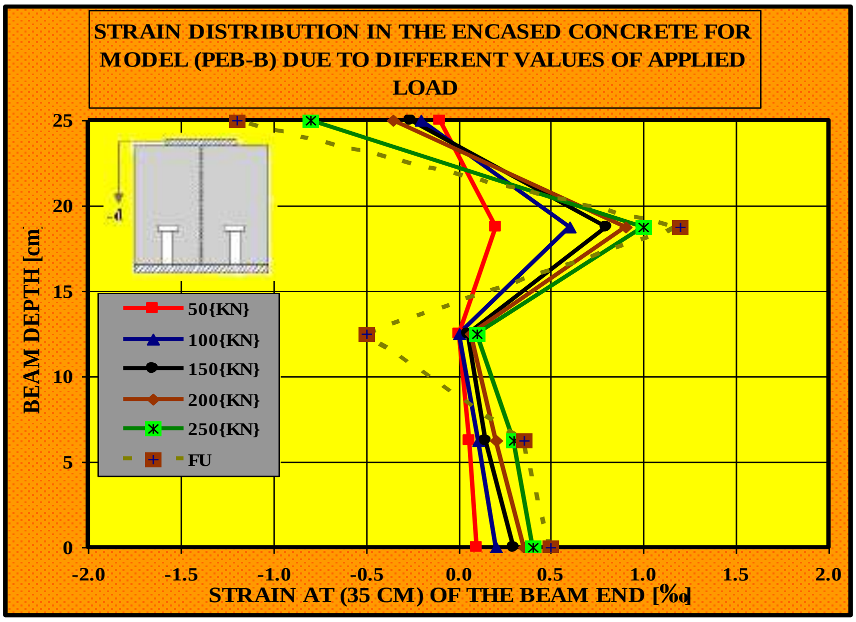


Fig. 16. Strain Distribution along the Depth of Encased Concrete for Model (PEB-B).

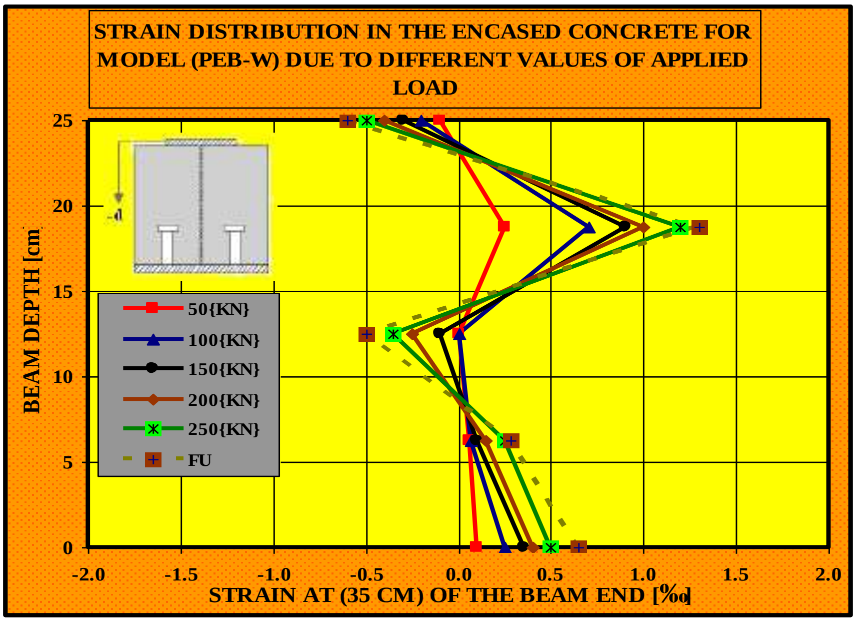


Fig. 17. Strain Distribution along the Depth of Encased Concrete for Model (PEB-W).

--EFFECT OF CONCRETE POISSON'S RATIO ON THE BEHAVIOR OF MODEL (PEB-W):

The composite partially encased beam (PEB-W) has been chosen to study the effect of variation of the concrete Poisson's Ratio on its behavior. This beam is described in details in (Figure 5). The beam (PEB-W) has an assumed concrete Poisson's Ratio equal to (ν=0.2) and it has been reanalyzed for values of (0.17 and 0.15). As shown in (Fig. 18). the ultimate load capacity of this beam has insignificant effect with reduction of Poisson's ratio value. The reduction in the ultimate load capacity is not more than (3 % and 5%) for the concrete Poisson's ratio values (0.17 and 0.15) respectively.

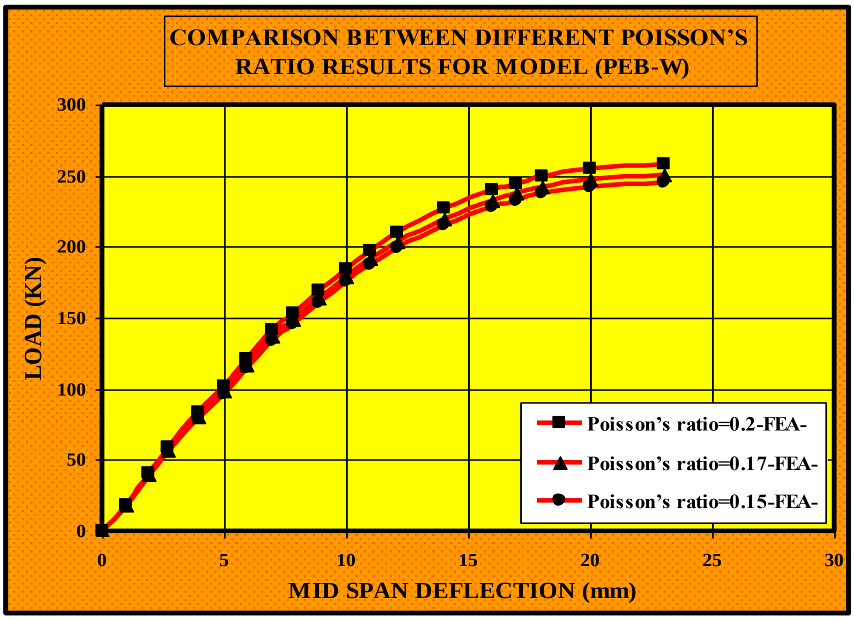


Fig. 18. Effect of Poisson's Ratio on the Behavior of Model (PEB-W).

- EFFECT OF THE COMPRESSIVE STRENGTH OF CONCRETE ON MODEL (PEB-B):

The composite partially encased beam (PEB-B) has been chosen to study the effect of variation of the compressive strength of concrete on its behavior. This beam is described in details in (Figure 5). The beam (PEB-B) has an experimental compressive strength of concrete equal to (46.540 N/mm2) and it has been reanalyzed for values of concrete compressive strength (f'_c) of (30, 60 and 70 N/mm2) as shown in (Fig. 19). The behavior of this beam with high compressive strength seems to be stiffer than those having smaller strength. The predicted ultimate load of this beam is increased by (12% and 18.1%) for concrete compressive strength values of (60 and 70)-(N/mm2), respectively, and reduced by (11.6%) for compressive strength value of (30 N/mm2) relative to the tested result.

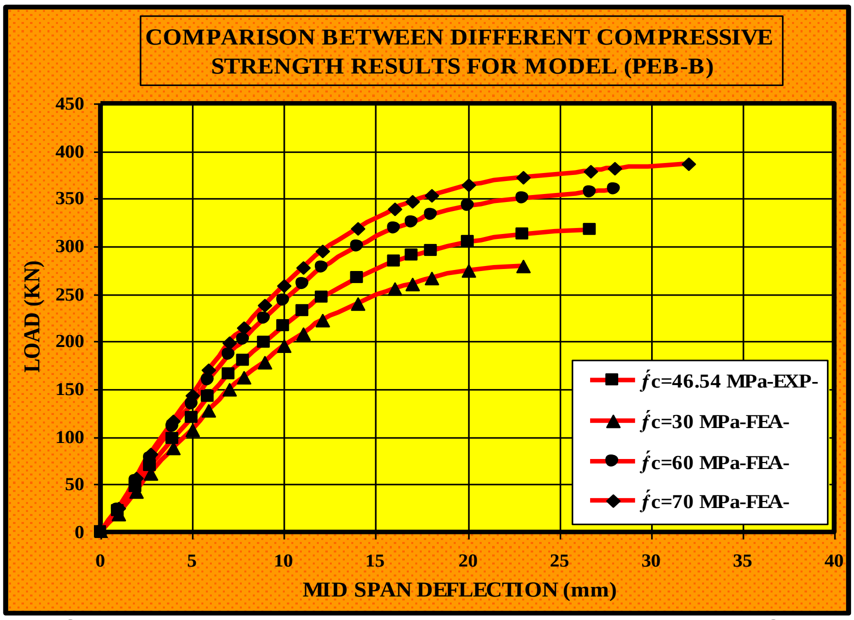


Fig. 19. **Effect of Concrete Compressive Strength on the Behavior of Model (PEB-B).**

* CONCLUSIONS:

Based on the results of this investigation, the following conclusions can be drawn:

1. The modeling of concrete by eight-node brick elements (**SOLID65** element), the I-steel section by the four-node shell element (**SHELL43** element), the steel reinforcement by two-node bar element (**LINK8** element), the shear stud by two-node nonlinear spring element (**COMBIN39** element) and the interface model by both (**SOLID65** element) on the surface of encased concrete and (**TARGE170** element) on the surface of steel section gives results which are close to the experimental results for the analysis of composite encased beams consisting of preflex steel section.
2. The failure load given by **ANSYS** computer program are close to that measured during experimental test.
3. The analyzed partially encased specimen with vertical studs {studs on bottom flange} are more efficient than the horizontal ones {studs on web} in providing the composite action between the steel profile and the concrete encasement, because the vertical stresses from concrete encasement acting on the surface of bottom flange and also the friction forces developed in the same surface is tremendously higher than that developed in the surface of steel section web.
4. According to the Applied load vs. End slip behavior, the specimens with headed studs can be considered ductile and the behavior is almost elastic-plastic, while the specimen without shear connectors slightly decreased in the applied load after the ultimate load capacity was reached. Therefore, both headed studs horizontally and vertically welded on the steel profile can be effectively used to provide composite action.
5. The values of strains at the steel-encased concrete surface (contact plane) for the models with full shear connection are nearly the same in comparative with the same model without shear studs were the strains values at the contact plane showing miner diverging.
6. The finite element results show that the Poisson's ratio has insignificant effect on the increasing or decreasing the ultimate load of the composite encased beams.

NOTATIONS:

1-D	One Dimensional Mode
2-D	Two Dimensional Mode
3-D	Three Dimensional Mode
Ec	Modulus of Elasticity of Concrete
Es	Modulus of Elasticity of Steel
f	Function
f'_c	Uniaxial Compressive Strength of Concrete
f_t	Uniaxial Tensile Strength of Concrete
P	Applied Concentrated Load
ε	Strain
ε_{cu}	Ultimate Strain
ν	Poisson's Ratio
τ	Shear Stress
Δ_p	Cambering Produced in the Steel Section
Δ	Deflection
y	Distance from the Steel Section Centroid to the Top Surface of Compression Plange
I	Moment of Inertia
M	Bending Moment

REFEENCES:

***** EUROCODE 4. In: Design of composite steel and concrete structures – Part 1-1: General Rules and rules for buildings. European Committee for Standardization; 2004.

***** ANSI/AISC 360-05. In: Specification for structural steel buildings. American Institute of Steel Construction; 2005.

***]** PR NBR 8800. In: Design of steel and composite structures for buildings. Brazilian Association of Standard Codes; 2007.

***** N. Roussel, S. Staquet, L. D'Aloia Schwarzentruber, R. Le Roy, and F. Toutlemonde, "SCC Casting Prediction for the Realization of Prototype VHPC-Precambered Composite Beams", Materials and Structures, Vol. 40, 2007, pp.877–887 .

***** Bernuzzi C, Zandonini R. In: Buckner D, Shahrooz BM, editors. Slim floor steel–concrete Composite systems. Composite construction in steel and concrete, vol. III. Germany: ASCE; 1996. p. 486–99.

***** Breuninger U. Design of lying studs with longitudinal shear force. In: International Symposium on connections between steel and concrete; 2001. p.1015–24.

***** Dipaola V, Prete F, Prete G. The elasto-plastic behaviour of encased composite beams for Slim floors in multi-storey buildings. In: 2nd international congress–Fib. Naples: FIB. 2006. p. 1–12 (ID 5-24).

***** Kuhlmann U, Kürschner K. Structural behaviour of horizontally lying shear studs. In: 5th International conference in composite construction in steel and concrete. South Africa; 2005. p. 534–43.

* Ju Y-K, Kim S-D. Structural behavior of alternative low floor height system using structural Tee, half precast concrete, and horizontal stud. Canadian J. Civil Engineering 2005;32(2):329–38.

* Hegger J, Goralski C. Structural behavior of partially concrete encased composite sections With high strength concrete. In: 5th international conference in composite construction in Steel and concrete. South Africa; 2005, p. 346–55.

* Silvana De Nardin, and Ana Lucia H.C. El Debs, "Study of Partially Encased Composite Beams with Innovative Position of Stud Bolts"Journal of Constructional Steel Research, March-2008, pp.1–9 .

* Swanson Analysis Systems, ANSYS. Online manual, version10.0 (2005) and Theory Reference.10th ed. Swanson Analysis Systems, s.1., s.d.

* Method of Manufacturing Preflex Beams", World Intellectual Property Organization (International Bureau), International Publication Number: WO 01/18319 A1, International Publication Date: 15 March 2001, pp 1-56.

* F.D. Queiroza, P.C.G.S. Vellascob, and D.A. Nethercota, "Finite Element Modeling of Composite Beams with Full and Partial Shear Connection", Journal of Constructional Steel Research, Vol.63, 2007, pp.505–521.