Performance of Composite Steel-Concrete Beams with Stud Shear Connectors under Periodical Loadings

Laith Khalid Al-Hadithy
. Civil Eng Dep
Al-Nahrain University/ Iraq
lthadithy@yahoo.com

Mohammed Safaa Jaafar
(M.Sc.) Civil Eng. Dep.
Al-Nahrain University/ Iraq
m_s_j_90@hotmail.com

Abstract

Behavior of composite beams with headed stud shear connectors subjected to monotonous and displacement controlled non-reversible repeated loadings has been evaluated through studying influences of the cross-sectional proportioning, the degree of partial interaction, and the level of ductile deformability in the post-yielding stage, in addition to the state of loading (whether monotonous or repeated). Eleven one-third scaled composite beams (with their push-out segments) were manufactured and tested in five pairs (each comprising the two loading cases representing one varying studied parameter) beside the single standard composite beam dedicated to verify accuracy of the test results by comparing them to the prototype ones (three authorized experimental and analytical investigations) where no distinction (other than 7 % difference) between the results of the three authorized refereed investigations (experimental, analytical and Eurocode) and the present one.

Regarding the flexural resistance in repeatedly loaded composite beams, it has been found that lowering the neutral axis (by adding bottom steel plate) has significantly increased the beam flexural resistance by an average of 24.7 %. Meanwhile, the intensity of headed studs distribution in stiffened repeatedly loaded composite beams has revealed a vital role in controlling the severity of the post-ultimate flexural weakening, where decreasing number of the headed studs to the half has increased the value of that unfavorite parameter by 160.58%. Furthermore, that specified decrease of headed stud intensity has lowered the advantageous residual cyclic flexural ductility by 19.37 % and 11.48 % without and with stiffening bottom steel plates, respectively. Regarding the effect of the lengthening the headed stud on behaviour of the repeatedly loaded composite beams it has been found that lengthening the medium-length headed studs by 72% has raised the flexural stiffness by 41.1 %, while it has decreased the residual cyclic slippage index by 54.3 %.

Keywords: Composite Integrity, T-beams, Periodical Loadings, steel plate, shear connector, fracture pattern.

1. Introduction

The steel and concrete are the two most vastly used materials in construction, especially for multi-story buildings and bridges. In composite bridge decks the efficiency of the shear connectors may be reduced due to withstand repeated or cyclic stresses. This phenomenon of decreased resistance of materials to repeated stresses is called "fatigue", and the material test by the application of such stresses is called fatigue test. There are two kinds of fatigue testing: endurance fatigue test and residual strength testing:

- **Endurance testing:** Endurance fatigue testing focuses on the endurance of a structure or component, i.e. how long the test specimen will last under cyclic loading. In most endurance tests the peak load is kept constant and a cyclic load of constant loading range is applied to the specimen. After N cycles the strength of the specimen has reduced to that of the peak load and failure occurs. The number of the cycles to the failure is called endurance.
- **Residual Strength Based Procedures:** In the endurance based testing procedure a fluctuating load is applied after a number of cycles of a certain range the component fails at the peak load. This peak load is lower than the static strength, which clearly indicates that the strength of the component has decreased during the repeated loading. In the residual strength based procedure, a specific loading history with a certain range are applied to the component up to failure. From this a so called failure envelope, a curve describing the loss of static strength, is plotted.

1.1 Research Significance and Scope.

Only few researchers have studied the effects of low-cycle fatigue on shear connectors. Almost all of the literature on the fatigue life of a shear connector has been based on the assumption that the shear connectors behave elastically under cyclic loading. This assumption is correct for most bridge spans. However, in long-span bridges or bridges with partial shear connection the shear connectors near the supports may deform beyond the elastic limit. The resulting effect is that those connectors will fail at a lower number of cycles than predicted using the elastic assumption.

The scope of this research is to study the behavior of composite steel-concrete beams under monotonic and repeated loadings. Hence, its main objectives are: Investigate their fatigue resistance and the failure modes that occur, inspect the performance of shear connectors during loading cycles, give an insight into the efficiency of partial interaction at interfaces, them evaluating the integrity characteristics, making a verification study using dimensionless analysis based on augmenting large-scale model, to prove the reliability of the tested full-scale physical models, and analysis, discussion and assessment of some special flexural parameters and integrity indices specialized in the periodic repeated loading.

2. Experimental Parameters and Diversity of Test Beams.

The variety of the manufactured scaled composite beams (consisting of eleven composite beams designated as CB-1- to CB-11- is based on the experimental investigation which founded on some principal parameters which are: the dimensional proportionality which controls level of the centroidal axis (whether within the concrete flange or below), this has been conducted by optional addition of a firmly attached wide bottom steel plate, degree of partial interaction, through variation of spanwise spacing of headed stud shear connectors, level of ductile deformability in the post-yielding stage, by varying lengths of the headed studs, and type of loading, whether monotonous or repeated, with latter being of various numbers of load cycles. Hence, the geometrical properties and the constitutional features upon which the manufactured composite beams were classified have load the diversity of the composite beams (eleven composite beams) identified in Table 1 below.

2.1 Details of Beam Specimen.

Scale of the simply supported composite beam specimens was approximately 1:3 of the composite beams submitted by Chapman and Balakrishnan (1964). Each beam consists of a top reinforced concrete slab, interconnect to an underneath steel I-section by headed stud shear connectors outstanding from the top flange of the steel I-section. The beams spanned 2000 mm with an I-section steel member of 100 mm depth, 4.3 mm flange thickness, 57 mm flange width and 3.65 mm web thickness, with the reinforced concrete slab being of 50 mm thickness and 400 mm width. The geometry and the details of the test specimens are shown in Fig. (1). If a firmly attached bottom steel plate - by welded – is used, it will be then of 80 mm width and 5.22 mm thickness.

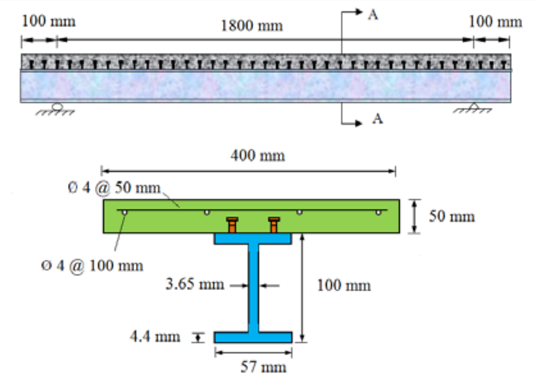

Figure 1: Typical simply supported beam layout (All dimension in mm).

2.2 Push-out Test Segments.

With reference to Fig. 2 and Plate 1 two standardly – proportional push-out segments (each for one used headed stud length) have been manufactured and tested. Arrangements for these tests were as per Eurocode 4 and IS: 11384-1985 but with scaled down by 1:2.6.

Table (3-1): The diversity of the manufactured test composite beams.

Specimen No.	Stud[(2)] overall length (mm)		No. of studs		Spacing in pairs (mm)		Type of loading		Bottom steel plate
	20	38	100	50	40	80	Monotonous	Repeated	
CB-1-[(1)]	•		•		•		•		
CB-2-	•		•		•		•		
CB-3-	•		•		•			•	
CB-4-	•		•		•		•		•
CB-5-	•		•		•			•	•
CB-6-	•			•		•	•		
CB-7-	•			•		•		•	
CB-8-	•			•		•	•		•
CB-9-	•			•		•		•	•
CB-10-		•		•		•	•		
CB-11-		•		•		•		•	

(1) Single load (midspan concentrated load).

(2) Unified shank diameter of 3.8 mm for all headed studs was used.

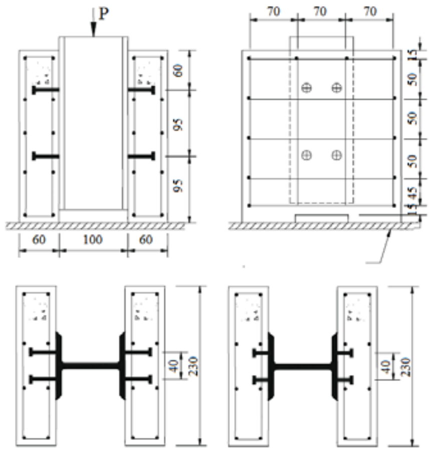

Figure 2: Push-out segments arrangements and geometry.

Plate 1: Push-out segments molds.

3. Testing Program.

3.1 Test Setup.

The supports and loading systems are the two main constituents of the present test set-up. The two supported ends of the all test specimens used in the testing program were fixed against vertical movement only by using rigid steel rig attached to the loading frame located to achieve a distance of 1800 mm center to center of support, put the supported very close and also used very thick plate to achieve a suitable base for push-out test, Plate (2) show a composite beam and push-out segment, respectively in their supporting and loading arrangements.

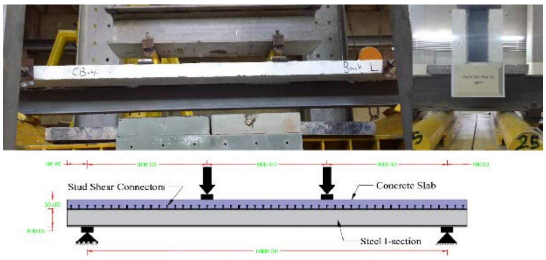

Plate 2: Typical test of composite beam and push-out segments.

3.3 Loading Process.

The test was controlled by displacement of the LVDT. Displacement control was used for the monotonic and repeated loading tests. The monotonic and repeated loading tests were conducted at a displacement rate of 0.005mm/s. The testing program was performed such one of each two similar test composite beams (representing one vary studied parameter) was tested under a monotonously increasing load, while the other under a periodically not reversing load (i.e. repeated loading) with a constant specified history for the five test composite beams involving repeated loading. That repeated loading history is shown in Fig. (3).

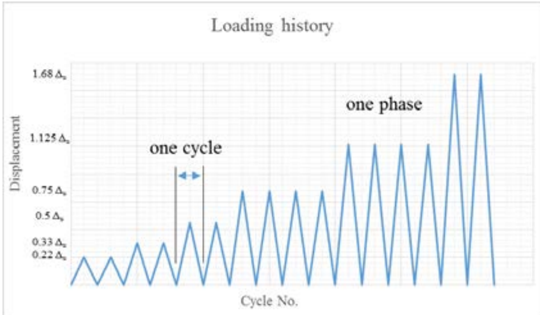

Figure 3: History of the repeated load

3.3 Data Recording:

the recording of the loads, displacements and lateral slip have to be started since the instant at which of the hydraulic jack came into contact with the specimen, where the first data record was equal to zero. In each repeated loading test, when the hydraulic jack was up to the required displacement, it was stopped then the stage of unloading was started and the hydraulic jack returned to the initial position where the read data of load was zero. Through all this stage the control system maintained all data recording for load and displacement. Then the second cycle was started followed by the third, fourth … etc but with new group of required displacement for each phase of loading and unloading.

4. RESULTS

4.1. Test Results of the Minor Specimens (Push-out Segments):

The load-slip relation for the two push-out segments is shown in Fig. (4), where the age of concrete at testing was 28days and its compressive strength was 68.3 MPa. From the two curve that shown in Fig. (4), the following output data are extracted:

- **The first push-out segment embracing 20 mm length headed studs:** the maximum shear resistance was 4.6658 kN per stud and the maximum slip at failure was 2.2589 mm. The failure mode was stud failure.

- **The second push-out segment embracing 38 mm length headed studs:** the maximum shear resistance was 7.22 kN per stud and the maximum slip at failure was 1.8245 mm. Finally, the failure mode also was stud failure. Plates (3) show the two push-out segments before and after testing.

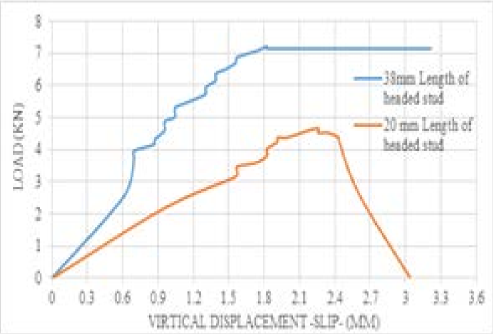

Figure 4: Load-slip relation for the segments.

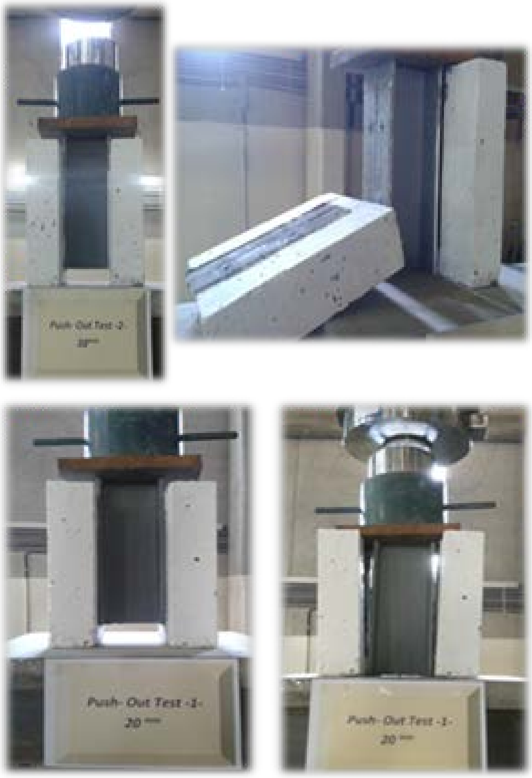

Plate 3: The first and the second push-out segments (of 20 mm and 38 mm length headed studs) subject to the standard test. (a) at of load application (b) at failure.

4.2 Presentation of the Prime Experimental Results:

The composite beams CB-1-, CB-2-, CB-4-, CB-6-, CB-8- and CB-10- were subjected to a vertical monotonic load until they exhibited severe damage where test results of each of those beams represent an independent parameter in the present comparative study. The age of concrete of the top flange in the tested composite beams at the time of testing was 28 days and the average of the compressive strength of concrete was 70.54 MPa (high strength concrete).

The load versus deflection beneath the load relations of the composite beams are shown in Figs. (5) and (6), while their load versus relative end slip relations are given in Fig. (7) and (8).

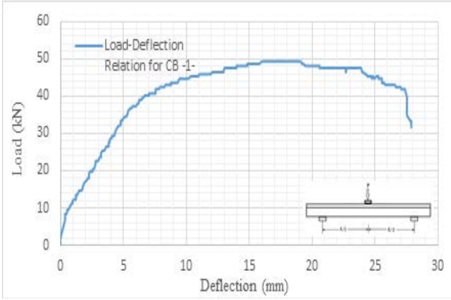

Figure 5: Load versus midspan deflection relation for the monotonously loaded composite beam CB-1-.

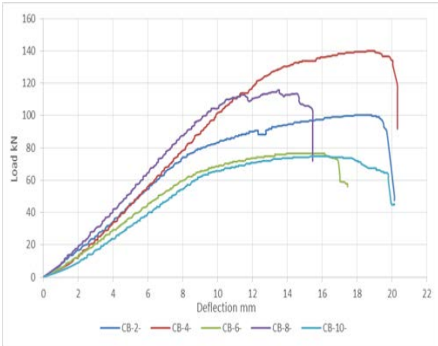

Figure 6: Load versus deflection relation for the monotonously loaded composite beam CB-2-, CB-4-, CB-6-, CB-8-, CB-10- respectively.

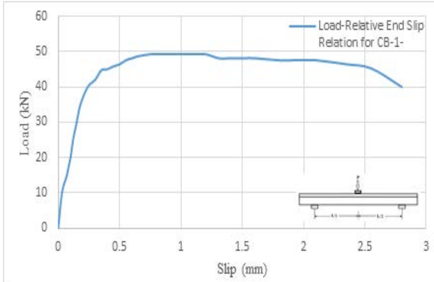

Figure 7: Load versus relative end slip relation for the monotonously loaded composite beam CB-2-, CB-4-, CB-6-, CB-8-, CB-10- respectively beam CB-1-.

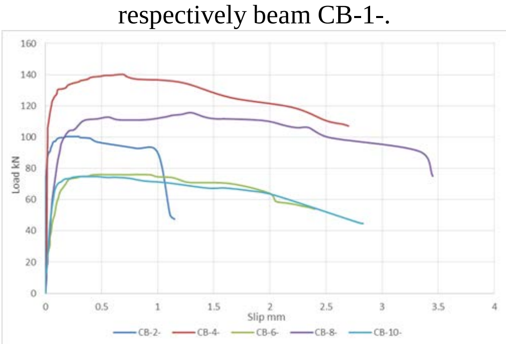

Figure 8: Load versus relative end slip relation for the monotonously loaded composite

4.2 Irreversible Periodic Loading Test Results:

The construction composite beams CB-3-, CB-5-, CB-7-, CB-9- and CB-11- were tested under irreversible periodic (i.e. repeated) loads as per loading histories shown in Fig. (3), where the results of each of those specimens represent an independent parameter in the present comparative study. The age of concrete of the top flange in the test composite beams at the time of testing was 28 days and the average of the compressive strength of concrete was 70.05 MPa. The load versus vertical deflection beneath the load relationships of the five specified composite beams are shown in Fig. (9) , while their load versus relative end slip relationships are shown in Fig. (10).

4.2.1 Failure mode: The composite beams subjected to either monotonous or displacement controlled non-reversible repeated loadings have all reached their limit states due to failure of the headed studs.

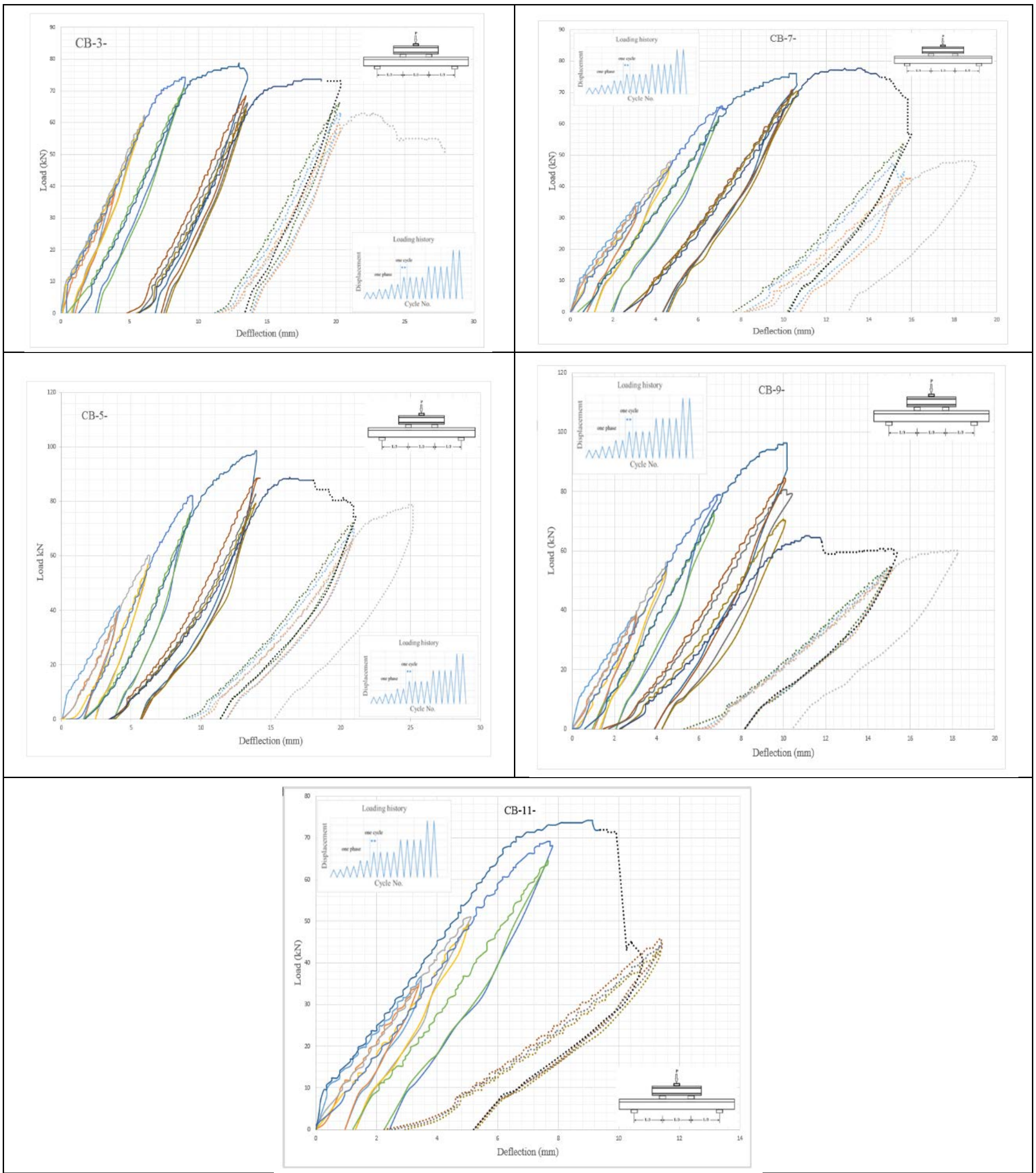

Figure 9: Load versus vertical deflection beneath the load responses till for the composite beams loaded by irreversible periodic repeated load as per attached loading history.

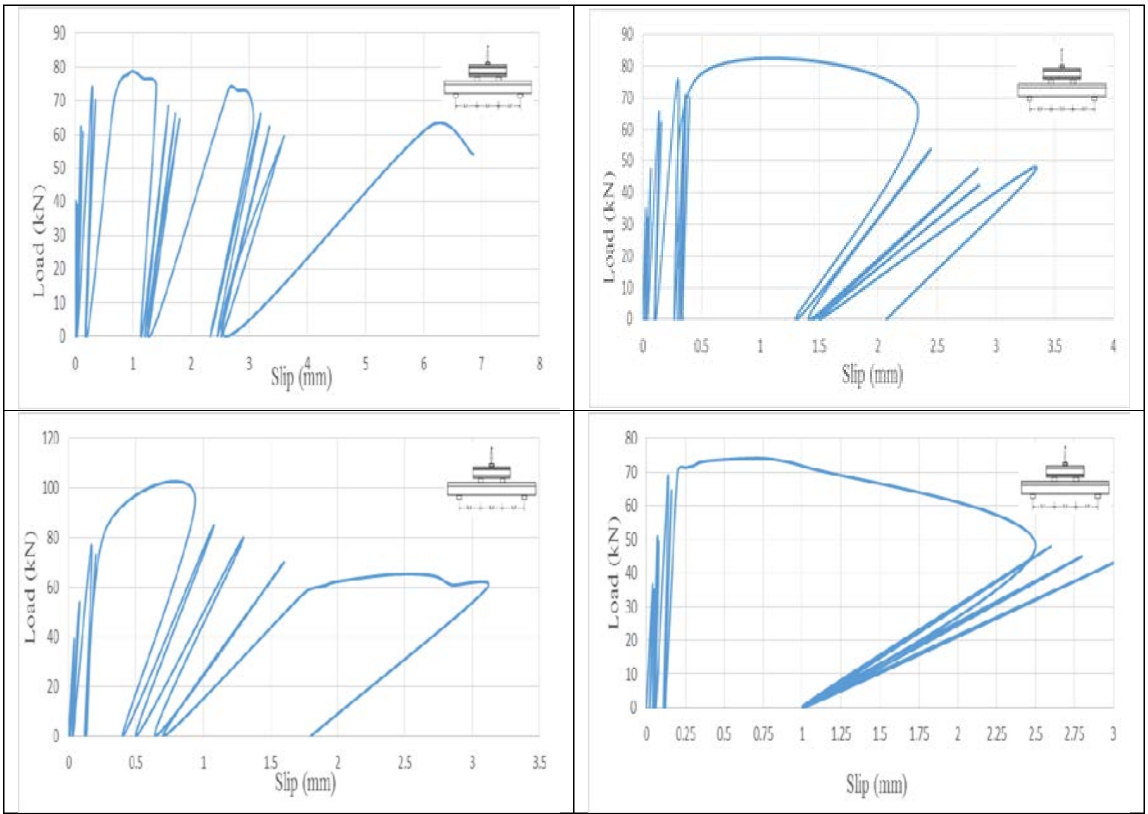

Figure 10: Load versus relative end slip relation for the composite beams CB-3-, CB-7-, CB-9-, and CB-11- respectively, loaded by irreversible periodic repeated load.

5 Verification Study:

The use of scale models in structural engineering offers the advantage of simulation for any component in a practical composite structure under controlled conditions, as it predicts the fundamental mechanisms operating in those components of the systems being investigated. Hence, the scale physical model has a more economical preference than the corresponding full-scale prototype. However, accuracy of the test results have to be verified by comparing them to the prototype ones in order to get a quantitatively reliable insight into the behavior of the composite system being investigated thus enabling the structural designer to benefit from such results and conclusions in practice.

5.1 First Respect of Verification: Correlation between Responses the Scaled Test Model and Full Prototype:

The evaluation of the accuracy and the assessment of the reliability of the test results of the present typical scaled composite beam - selected for verification purpose – have been based on a non-dimensional correlation with results of two investigations on a specified full size composite beam synonymous to the selected scaled test beam of the present verification study. One of those two reference investigations - on the specified full size composite beam – is an experimental one, while the other is a theoretical. Identification for each of those two reference investigations is given herein: (1) the experimental reference investigation; the work of (Chapman and Balakrishnan, 1964): who carried out a series of experimental test to illustrate the behavior of composite beam. (2) The theoretical reference investigation; the work of Hama (2014) which is solely based on the solution of Al-Amery and Roberts where the basic differential equations of equilibrium and compatibility were reduced to a single second order differential equation in term of interface slip between concrete and steel. Then, in order to considerate the nonlinear behavior of steel, concrete and shear connectors. The exact solution was obtained by considering appropriate boundary conditions according to load types and location.

5.1.1 Results and Assessment of the First Verification Respect:

With reference to Table (2), which shows the absolute - dimensional – values of the ultimate load and its accompanying midspan deflection, then the correspond dimensionless values as obtained by the two reference investigations (one is experimental and the other is theoretical) beside those of the present selected typical scaled test composite beam, very high agreement is obtained as none of the differences between the various dimensionless outputs and those of the present scaled test beam, exceeds 5%.

5.2 Second Respect of Verification: Comparison between the Results of the Present Scaled Test Beam and the Eurocode 4 Analysis Method for Composite Beams:

In this part, a typical composite I-section beam is analyzed in the aspect shown in Fig. (1), using the materials specified in the tested composite beams. For the present typical scaled test composite beam model selected for verification, the analysis procedure runs in the sequential steps [1].

Table (2): The actual and the dimensionless values of the ultimate load and deflection extracted from the two refereed investigations in addition to the scaled model of the present verification study and the corresponding multipliers.

	Actual Ultimate Load (kN)	Dimensionless Ultimate load			Actual Ultimate Deflection (mm)	Dimensionless Ultimate Deflection		
		Multipliers	value	% of difference from model		Multipliers	value	% of difference from model
Chapman and Balakrishnan's prototype (1964)	513	$\frac{L^2}{EI\delta}$	9.795	3.59	75	$\frac{EI}{PL^3}\times 10^3$	102.08	3.47
Theoretical nonlinear analysis (Hama, 2014)	525		9.764	3.26	77		102.409	3.16
Reference large scale physical model (present study)	49.24		9.455	0	15.99		105.76	0

5.2.1 Assessment of the Second Respect of Verification:

The results of ultimate load behavior of composite beam according Eurocode 4 (based on Johnson's Analysis and Assumptions) gives very close agreement with the results of the typical present scaled test composite beam for verification as the difference is less than 7% in the ultimate load carrying capacity or the corresponding deflection.

5.3 Concluding Remark:

Based on the outcomes of the two respects of of the verification study on the accuracy of the present experimental investigation, it is concluded that present experimental investigation is quite accurate where no distinction between the results of all the four investigations (three refereed and the present one) can be extracted.

6. Interpretation, Analysis and Discussion of Results

In this part, provides an extensive overview for the interpretation, analysis, discussion and assessment of the experimental test results presented in detail in the previous paragraph.

6.1 Pure Shear Performance of the Headed-Stud Interfaces.

Determination of shear stiffness and the energy absorbility (represented by modulus of shear toughness) are of importance for engineers who are involved in performance evaluation of stud shear connectors. Those characteristics as obtained experimentally are given in Table (3) and the effect of shank length of headed stud on its shear stiffness and modulus of shear toughness with their percentages of variation are shown in Figs. (11) and (12), respectively.

Table (3): "Shear Stiffness" and "Modulus of Shear Toughness" per headed stud for the two push-out segments comprising headed studs of diverse shank lengths(1).

Push-out Segment No.	Headed Stud Shank Length (mm).	P_u(2) (kN)	Slip at Ultimate Stage (mm)	K_s(3) (kN/mm)	M.O.S.T.(4) (kN/mm)
1	20	4.66	2.258	4.4629	8.1789
2	38	7.22	1.824	5.1277	17.4389

(1) As per the graphical load-slip relationships (per headed stud) shown in Fig.(4-2) for the two push-out segments.

(2) Ultimate load per headed stud.

(3)"shear Stiffness" per stud, which is equal to the numerical result of dividing *0.5* P_u by the value of the accompanying displacement.

(4) "Modulus of Shear Toughness" per stud, which is equal to the area under the curve of (shear force per stud versus slip) for the test of the relevant push-out segment presented in Fig. (4-2).

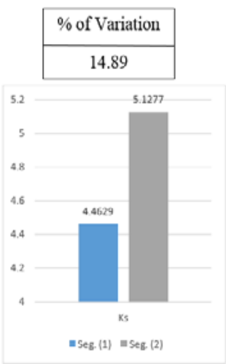

Figure (11): Effect of the shank length of the headed stud on its shear stiffness in push-out test

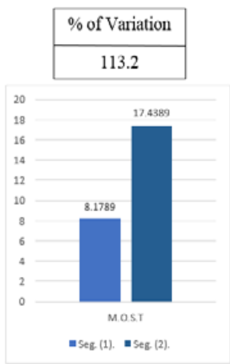

Figure (12): Effect of the shank length of the headed stud on its energy absorbility (represented by modulus of shear toughness) in push-out test

6.2 Performance of the monotonously loaded composite beams:

The comprehensive interpretation of the drawn experimental results for the six test composite beams monotonously loaded up to failure are given in Table (4).

The addition of a firmly attached wide bottom steel plate causes an increase in the ultimate load capacity and average flexural stiffness in both cases of high and low intensities of the headed studs distributions. However, such stiffening causes considerable decreases in the average anti-slip stiffness attaining 40.1 % for abundant headed stud provisions.

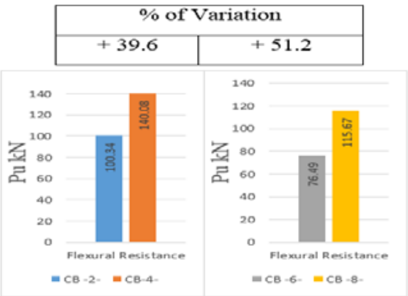

Figure (13): Effects of the proportions of the cross-section (dependent on strengthening by bottom steel plate) on the flexural resistance (represented by the ultimate load capacity P_u) for the monotonously loaded test composite beams

The ultimate load capacity and the average flexural stiffness of the composite beams decrease with decreasing the number of headed stud shear connectors (from 100 to 50 headed studs). Excepted from that finding is the average flexural stiffness of the composite beams provided by firmly attached wide bottom steel plates and few numbers of headed stud shear connectors where the decrease is limited to 14 %. Such decreases in the degree of partial interaction cause a reductions in the average anti-slip stiffness.

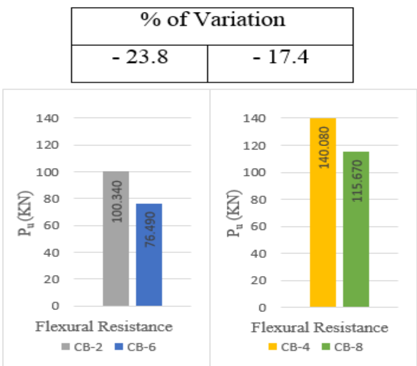

Figure (14): Effect of the shear-connection intensity (i.e. number or spacing of stud shear connectors) on the flexural resistance (represented by ultimate load capacity P_u) for the monotonously loaded test composite beams.

It can be clearly concluded that the increases in the overall lengths of the headed stud shear connectors lead to lowering values of the ultimate load capacity and the average flexural stiffness 2.22 % and 11.05 %, respectively. Meanwhile, such increases (in the headed stud length) effectively raise values of the average anti-slip stiffness up to 53.04 %.

Table (4): Comprehensive interpretation of the drawn experimental results for the six test composite beams monotonously loaded up to failure

Beam Mark [1]	Flexural Behavior								Integrity Level		AASS / AFS
	P_y [2] (kN)	P_u [3] (kN)	P_y / P_u	Δ_y [2] (mm)	Δ_u [3] (mm)	IFS [4] (N/mm)	AFS [5] (N/mm)	FD [6] (Ratio)	δ_u [7] (mm)	AASS [8]	
CB-1	40.1654	49.24	0.8157	6.6898	15.98	6.0039	3.0813	2.3886	0.75	65.6533	21.3066
CB-2	80.4727	100.34	0.8019	9.2093	17.89	8.7381	5.6087	1.9425	0.3	334.4666	59.6333
CB-4	112.832	140.08	0.8054	11.294	18.59	9.9899	7.5352	1.6459	0.7	200.1142	26.5571
CB-6	65.1445	76.49	0.8516	8.9487	13.98	7.2797	5.4713	1.5622	0.72	106.2361	19.4166
CB-8	104.316	115.67	0.9018	9.6437	13.46	10.8169	8.5936	1.3957	1.3	88.9769	10.3538
CB-10	63.4414	74.79	0.8482	9.3831	15.37	6.7612	4.8659	1.6380	0.46	162.5869	33.4130

(1) With reference to Fig. (3-1).
(2) Applied load and deflection at the stage of yielding of the steel I-beam bottom flange (i.e. at end of the linear stage).
(3) Applied load and deflection at the ultimate stage
(4) Initial flexural stiffness which is equal to the slope of the linear (initial) stage of the load-deflection curve for the specified beam [Figs.(4-3) and (4-4)]
(5) Average flexural stiffness = P_u/Δ_u
(6) Flexural ductility = Δ_u/Δ_y
(7) Relative horizontal end slip at steel-concrete interface at ultimate stage.
(8) Average anti-slip stiffness = P_u/δ_u

6.3. Performance of the repeatedly loaded composite beams:

The flexural behavior and the integrity state, where some principle physical and mechanical interpretations have been carried out on the directly measured response of the eleven laterally loaded test composite beams to introduce specialized properties within those two main phases. They are all presented in Table (5).

Table (5): Interpretation of the drawn experimental results for the five test composite beams subjected to displacement-controlled non-reversed repeated loading [1].

Beam Mark [2]	U.L. [3] Cycle No.	P.I.F [4] Cycle No.	Flexural Behavior							Integrity State			
			P_u^* [5] (kN)	P_{PIF}^* [6] (kN)	PUFW [7] (%)	Δ_u^* [5] (mm)	AFS* [8] (kN/mm)	Δ_{PIF}^* [6] (mm)	RCFD [9]	δ_u^* [10] (mm)	AASS* [11] (kN/mm)	S_{PIF}^* [12] (mm)	RCSI [13]
CB-3-	7	11	78.76	73.66	6.47	12.94	6.084	18.766	1.450	1	78.76	2.65	2.65
CB-5-	7	11	98.63	86.14	12.66	13.9	7.095	18.158	1.306	-	-	-	-
CB-7-	11	11	77.53	74.22	4.26	12.85	6.029	15.03	1.169	0.48	161.52	1.5	3.125
CB-9-	7	11	96.36	64.57	32.99	10.07	9.569	11.642	1.156	0.94	102.51	2.71	2.88
CB-11-	7	7	74.22	71.38	3.82	9.035	8.214	9.9	1.095	0.7	106.02	1	1.428

(1) As per the displacement history shown in Fig. (4-1).
(2) With reference to Table (3-1).
(3) Number of the cycle (of the repeated displacement history) which includes the ultimate load.
(4) Number of the cycle (of the repeated displacement history) which includes entire decay of the partial interaction.
(5) The maximum (i.e. ultimate) load value and its corresponding deflection value.
(6) The load value (in the P.I.F) cycle at instant of the entire partial interaction decay, and its corresponding deflection value.
(7) Percentage of the "Post Ultimate Flexural Weakening" = $[(P_u^* - P_{PIF}^*)/P_u^*] \times 100\%$.
(8) "Average Flexural Stiffness" = P_u^*/Δ_u^*
(9) "Residual Cycle Flexural Ductility" = $\Delta_{PIF}^*/\Delta_u^*$
(10) Relative horizontal end slip at steel-concrete interface (containing headed studs) that accompanies P_u^* and Δ_u^*.
(11) "Average Anti-Slip Stiffness" = P_u^*/δ_u^*
(12) Relative horizontal end slip at steel-concrete interface (containing headed studs) that accompanies P_{PIF}^* and Δ_{PIF}^*
(13) "Residual Cycle Slippage Index" = $\delta_{PIF}^*/\delta_u^*$

6.3.1 Flexural Resistance (represented by ultimate load capacity Pu*) of Composite Beams Subjected to

Displacement Controlled Non-reversible Repeated Loading:

Addition of a firmly attached wide bottom steel plate causes an increase in the ultimate load capacity (Pu*) in both cases of high and low intensity of headed stud distribution.

% of Variation	
+ 25.2	+ 24.2

Figure (15): Effect of the proportions of the cross-section (dependent on strengthening by bottom steel) on the flexural resistance (represented by ultimate load capacity P_u^*) for the composite beams subjected to displacement controlled non-reversible repeated loading.

Effect of the degree of partial interaction was very small, where decreasing of the number of headed studs from 100 to 50 headed studs causes a slight reduction in the ultimate load capacity not exceeding 1.56 % in the normal - unstiffened case, and 2.3 % in the superior case of stiffening by a firmly attached wide bottom steel plate.

It is observed that the excessive increase in the lengths of headed stud shear connectors causes slight reduction in the ultimate load capacity not exceeding 4.26 %.

The ultimate load capacity of composite beams subjected to displacement controlled non reversible repeated loading are lower than the ultimate load capacity of similar beams subjected to monotonously applied loading.

% of Variation				
- 21.5	- 29.5	- 1.3	- 16.6	- 0.7

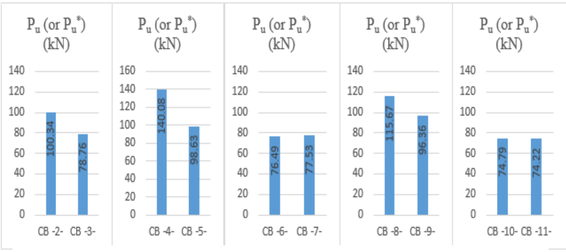

Figure (16): Effect of the type of load (monotonous or repeated) on the flexural resistance [represented by ultimate load capacity P_u or P_u^*] for the test composite beams.

6.3.2 Post-Ultimate Flexural Weakening (PUFW):

Close inspection clarifies that the addition of a firmly attached wide bottom steel plate causes an increase in the percentage of post-ultimate flexural weakening in both cases of high and low intensities of provided headed studs.

% of Variation	
+ 95.67	+ 674.41

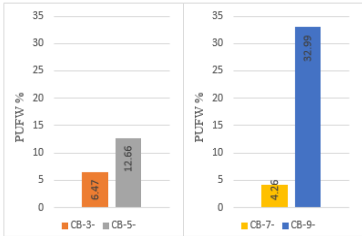

Figure (17): Effect of the proportions of the cross-section (dependent on strengthening by bottom steel) on the percentage of post-ultimate flexural weakening (PUFW), for the composite beams subjected to displacement controlled non-reversible repeated loading.

The post-ultimate flexural weakening of composite beams decreases with lessening the headed stud shear connectors by 34.15 % for unstiffened composite beams, while the addition of a firmly attached wide bottom steel plate highly increase value of the post-ultimate flexural weakening upto 160.58 %.

The percentage of post-ultimate flexural weakening (PUFW) of the composite beams decreases with increasing overall lengths of headed stud shear connectors.

% of Variation
- 10.32

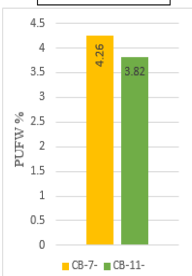

Figure (18): Effect of the overall length of the headed stud shear connectors on the percentage of post-ultimate flexural weakening (PUFW), for the composite beams subjected to displacement controlled non-reversible repeated loading.

6.3.3 The Average Flexural Stiffness:

It is observed that addition of a firmly attached wide bottom steel plate to composite beams subjected to displacement controlled non-reversible repeated loading causes an increase in the average flexural stiffness.

Very small effect of the degree of partial interaction on the cyclic flexural resistance (represented by average flexural stiffness; AFS) without addition of a firmly attached wide bottom steel plate not exceeding 0.88 % is detected. On the other hand, lowering the degree of partial interaction causes a significant increase in the flexural parameter attaining increase 34.85 % due to the addition of a firmly attached wide bottom steel plate.

The average flexural stiffness of the composite beams effectively increases upto 41.1 % with lengthening the headed stud shear connectors.

The general impression of the effect of the non-reversible repeated loading is a moderate increase of the cyclic flexural resistance (represented by average flexural stiffness; AFS) at a rate of (10 %), except for composite beams embracing long headed studs where rather high increases (reaching 68.8 %) on the average flexural stiffness; AFS values are observed.

6.3.4 The Residual Cyclic Flexural Ductility:

Very small effect of the addition of a firmly attached wide bottom steel plate with the lower degree of partial interaction on the residual cyclic flexural ductility is detected, where it does not exceed 1.11 %. On the contrary, the effect becomes significantly larger with the higher degree of partial interaction where the decrease in the residual cyclic flexural ductility attains 9.9 %.

It is observed that the residual cyclic flexural ductility of the composite beams subjected to displacement controlled non-reversible repeated loading decreases with decreasing the number of headed stud shear connectors.

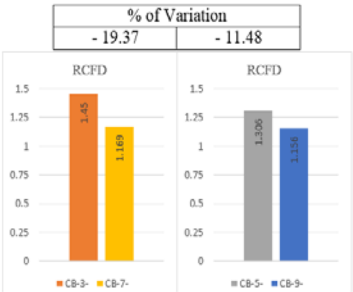

Figure (19): Effects of the shear connectors' intensity (i.e. number or spacing of stud shear connectors) on the residual cyclic flexural ductility for the composite beams subjected to displacement controlled non-reversible repeated loading.

It is also noticed that the residual cyclic flexural ductility of the composite beams decreases with increasing lengths of the headed stud shear connectors by 6.33 %.

6.3.5 Integrity Preservation, and Average Anti-Slip Stiffness:

Clearly detected that addition of a firmly attached wide bottom steel plate and increasing lengths of the headed stud shear connectors for composite beams subjected to displacement controlled non-reversible repeated loading causes a decreases in the average anti-slip stiffness.

It can be observed that the average anti-slip stiffness of the composite beams increases with decreasing the number of headed stud shear connectors from 100 to 50 headed studs.

Insignificant effect of the load duration on the average anti-slip stiffness is detected, where it cannot devise any specific behaviour for the average anti-slip stiffness of composite beams.

6.3.6 Integrity Preservation; and Residual Cyclic Slippage Index:

The addition of a firmly attached wide bottom steel plate and the lengthening of headed stud shear connectors for composite beams subjected to displacement controlled non-reversible repeated loading causes a decreases in the residual cyclic slippage index (RCSI). Meanwhile, the residual cyclic slippage index increases with decreasing the number of headed stud shear connectors from 100 to 50.

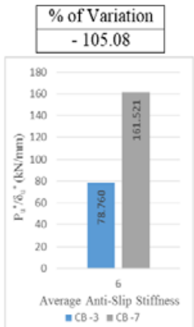

Figure (20): Effects of the shear-connectors intensity (i.e. number or spacing of stud shear connectors) on the average anti-slip stiffness P_u^*/δ_u^* for the beams subjected to displacement non-reversible repeated loading.

7. Conclusions

In this study, the behaviour of composite beams subjected to monotonous and displacement controlled non-reversible repeated loadings has been investigated. The influences of the dimensional proportionality (which controls level of the centroidal axis), the degree of partial interaction, the level of ductile deformability in the post-yielding stage, and - at last - the type of loading (whether monotonous or repeated) have been taken into consideration. The ultimate load capacity, average flexural stiffness, the average anti-slip stiffness, the post-ultimate flexural weakening, the residual cyclic flexural ductility and the residual cyclic slippage index have also been discussed.

However, accuracy of the test results (for one typical scaled physical composite beam) have to be verified by comparing them to the prototype ones (three authorized experimental and analytical investigations) in order to get a quantitatively reliable insight into the behavior of the composite system being investigated thus enabling the structural designer to benefit from such results and conclusions in practice.

7.1 Conclusions Drawn From the Verification Study:

- Very high agreement - between the present largely scaled physical typical composite beam model and each of the authorized experimental and analytical investigation - is obtained. This finding is realized as none of the differences between the two reference dimensionless outputs (one is experimental and the other is theoretical) and those of the present selected typical scaled test composite beam, exceeds 5%.

- Results of the ultimate load behaviour of composite beams according Eurocode 4 (based on Johnson's analysis and assumptions) gives efficiently close agreement with the results of the present typical largely scaled test composite beam for verification as the difference is less than 7% in the ultimate load carrying capacity or the corresponding deflection.

7.2 Conclusions Drawn from Prime Experimental Investigation:

- It has been noted in pure shear performance of the headed-stud interfaces that when the shank of the headed stud is shorter, strength degradations after the peak load become more severe leading to decreases in its shear stiffness and energy of absorbility.
- Stiffening the composite beams by wide bottom steel plate and/or increasing the degree of partial interaction is the single means to increase the strength of the composite beams with headed stud shear connectors subjected to monotonic loading.
- To avoid the increase of the degree of partial interaction as the singular means to increase the strength of the composite beams with headed stud shear connectors subjected to displacement controlled non-reversible repeated loading, the stiffening by bottom wide steel plate emerges as the competitive and even the best technique for this purpose.

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أداء العتبات المركبة من الحديد والخرسانة المزودة بروابط قص مسمارية تحت تأثير الاحمال الدورية

أ.م.د.ليث خالد الحديثي
قسم الهندسة المدنية
جامعة النهرين

م. محمد صفاء جعفر
قسم الهندسة المدنية
جامعة النهرين

الخلاصـــة

يعنى التحري التجريبي الحالي بتقييم سلوك العتبات المركبة المزودة برباطات قص مسمارية التي تتعرض للأحمال الراتبة و الاحمال المتكررة المسلطة على شكل ازاحة بأتجاهٍ واحدٍ.

لغرض دراسة تأثيرات تناسب الأبعاد (تتحكم بمستوى المحور المحايد) ودرجة التداخل الجزئي ومستوى التشوه المطيلي في مرحلة ما بعد الخضوع - وفي الاخير- نوع التحميل (سواء كان راتباً او متكرراً). حيث تم تصنيع نموذجين اثنينِ من الـ (push-out segment) وأحد عشر نموذجاً (بنسبة أبعاد أصغر scaled) من العتبات المركبة. تمثل تلك العتبات المركبة بسيطةُ الاسنادِ نموذجاً مصغر الابعاد بنسبة 1:3 من العتبة المركبة المقدمة من قبل Chapman و Balakrishna (1964).

تم تنفيذ البرنامج العملي بحيث ان كل عتبتين مركبتين متماثلتين (اللتين تمثلان معاملاً واحداً من العوامل المطلوبة دراستها) يتم فحص احداهما تحت تأثير الاحمال الراتبة بينما يتم فحص الاخرى تحت تأثير الاحمال الدورية احادية الازاحة وبنمط تحميل موحد لكلٍ من العتبات المركبة الخمسة المشمولة بالتحميل المتكرر.

لقد تم التحقق من دقة نتائج الاختبار (لعتبة مركبة مصغرة نموذجية واحدة) من خلال مقارنتها بنماذج لعتبات مركبة اخرى (ثلاثة دراسات لنماذج عملية وتحليلية) من أجل الحصول على نظرة موثوقة من الناحية الكمية في سلوك العتبات المركبة التي تمت دراستها والتحقيق منها و بذلك تمكن المصمم الانشائي من الاستفادة من تلك النتائج والاستنتاجات في الممارسة العملية و أعمال التصميم. أستناداً إلى النتائج المستحصلة من اثنتين من دراسات التحري عن دقة التحري التجريبي الحالي أستُنتج انهُ ذو دقة عالية حيث أن الأختلاف بينَ نتائج التحريات الموثوقة المحكِمة الثلاث (التجريبي والتحليلي والكود الاوربي) وبين التحري التجريبي الحالي لا يتجاوز 7 %.

تم الاخذ بنظر الاعتباركلٍ من المقاومة القصوى للتحمل ومتوسط الصلابة الانثنائية ومتوسط الصلابة المضادة للانزلاق والضعف ما بعد الانثناء النهائي والضعف الانثنائي الدوري المتبقي ومؤشر الانزلاق الدوري المتبقي .. و ذلك ضمن التحليل والمناقشة وتقييم نتائج الاختبار التجريبي. فيما يتعلق بالمقاومة الانثنائية للعتبات المركبة ذات التحميل الدوري وجد ان تخفيض مستوى المحور المحايد (بواسطة اضافة صفيحة حديدية سفلى) يسبب زيادة كبيرة في المقومة الانثنائية للعتبة تصل الى 24.7 % كمعدل وسطي. وفي الوقت ذاته فأن كثافة روابط القص تمتلك دورً حيويً في السيطرة على معامل الضعف ما بعد الانثناء النهائي في العتبات المركبة المقواة ذات الاحمال الدورية حيث ان تقليل عدد روابط القص الى النصف يزيد من قيمة هذا المعامل غير المرغوب بمقدار 160.58 %. علاوةً على ذلك فأن هذا النقصان في عدد روابط القص أدى الى تخفيظ الضعف الانثنائي الدوري المتبقي المفيد بنسبتي 19.37 % و 11.48 % بدون او مع صفيحة التقوية الحديدية السفلى على التوالي. أما في ما يتعلق بتأثير اطالة روابط القص على سلوك العتبات المركبة ذات الاحمال الدورية فقد وجد ان إطالة روابط القص بنسبة 72 % يسبب زيادة في الصلابة الانثنائية بنسبة 41.1 % في حين أن هذه الزيادة في الطول تعمل على تخفيض مؤشر الانزلاق الدوري المتبقي بنسبة 54.3%.