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Floor Beams Reinforcement Effect on the Spandrel Beams

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Abstract: This paper investigates the effect of steel reinforcement of the floor beams on the analysis results of different floor to spandrel length and depth ratios(lf/ls) (hf/hs). This study investigates the behavior of seven full-scale spandrel-floor beams using nonlinear three-dimensional finite element analysis via ANSYS 14.0. The results reveal that positive reinforcement in the floor beams significantly enhances performance, particularly after cracking, by redistributing internal stresses and allowing torque to transfer back to the floor beams. This interaction leads to increased load-carrying capacity and reduced deflection without altering concrete cross-sections. Ultimately, the findings highlight the importance of reinforcement strategies that satisfy both structural and economic requirements for optimizing spandrel-floor beam assemblies.

Keywords: *Spandrel-Floor Beams, Compatibility Torsion, ANSYS 14.0.*

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I. INTRODUCTION

Spandrel beams are typically situated at the perimeter of a building, spanning between columns and often supporting floor or roof slabs or beams. In addition to shear forces and bending moments, spandrel beams may experience twisting about their longitudinal axes—a phenomenon known as compatible torsion—especially when external loads are applied away from the vertical plane of bending. The interaction between the floor and spandrel beams adds complexity to the situation, making it significantly different. The spandrel-floor beam assembly can be viewed as a statically indeterminate structure subjected to a complex distribution of stresses resulting from multidirectional forces, including axial forces, torsion, bending moments, and shear. The behavior and design procedures for spandrels vary considerably between the pre-cracking and post-cracking stages. To simplify the situation, considering a rectangular cross-sectional reinforced beam under pure torsion only. The variation of torsional shear stress (τ) along redial lines in the cross-section can be shown in Fig. (1). It can be observed that the maximum shear stress (τmax) occurs at the middle of the longer side. The two-dimensional state of stresses at any point within the beam can be expressed by the principal stresses (σ1) and (σ2). Mohr's circles of stresses are widely used to investigate the state of stresses. Before cracking, the concrete resists the torsional stresses and the steel is virtually unstressed. Therefore, the elastic analysis of the uncracked section can be considered to estimate the torque. In the other hand, if one of the principal stresses reaches to the tensile strength of the member then torsional cracks began to generate perpendicular to the direction of the maximum principal stresses. The first torsional cracks can be noticed in the middle of the longer side of the beam surface since there is maximum concentration of torsional stresses.

The second torsional cracks can be observed in the middle of the shorter side face. These kinds of cracks will continue until they generate spiral torsional cracks that responsible of failure. In structures, the stresses are more complicated since they are not under pure torsion only.

At post-cracking stage, the spandrels behaviour will be different from that of pre-cracking stage, the reinforcement bars will be activated and act as ties carrying the tension while the concrete forms struts carrying compression. This phenomenon forms a space truss analogy [2]. As illustrated in Fig. (1-a), shear stress is greater near the outer edges of a concrete element than in its core. Consequently, compressive stress is primarily concentrated in this peripheral zone, a behavior known as thin-walled tube behavior [1]. The thickness of the wall is the shear flow zone, where the shear flow is assumed to be constant. The portion of concrete inside the shear flow zone can be neglected in calculating the capacity.

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Skew bending theory [3] is another theory, which can be applied to members under flexural moments as well as torsion, such as spandrels. This theory explain that the flexural moment and the torsional moment will combine to generate a resultant moment inclined to the axis of the beam. This resultant will affect by magnitude of flexural moment and torsional moment causing three possible modes of failure: Mode (1), Modified Bending Failure, this observed when the magnitude of flexural moment is larger than torsional moment. In mode (2), Lateral Bending Failure can be observed in beams with thin web since the effect of flexural moment and torsion are comparable. Mode three was proposed by Walsh et al and Collins et al [4,5], in which the torsion had a significant interaction with bending moment.

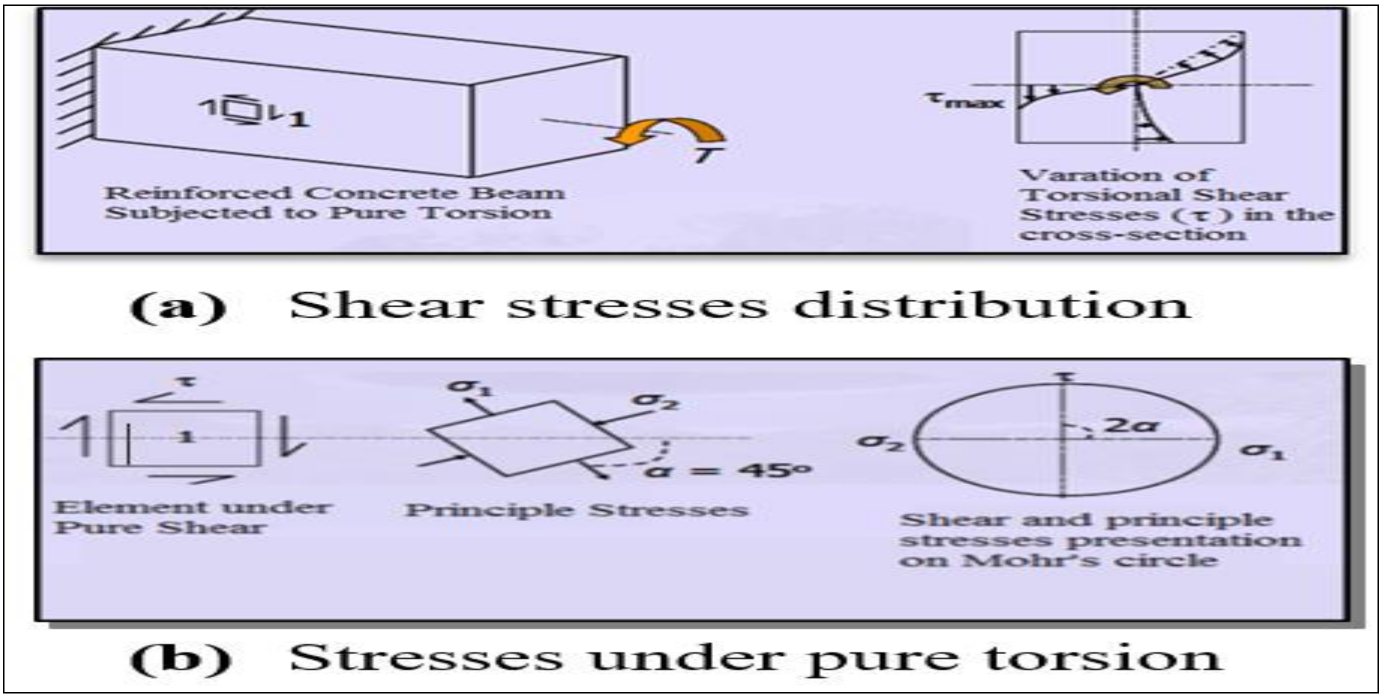

Fig 1: Reinforced Concrete Element Subjected to Pure Torsion

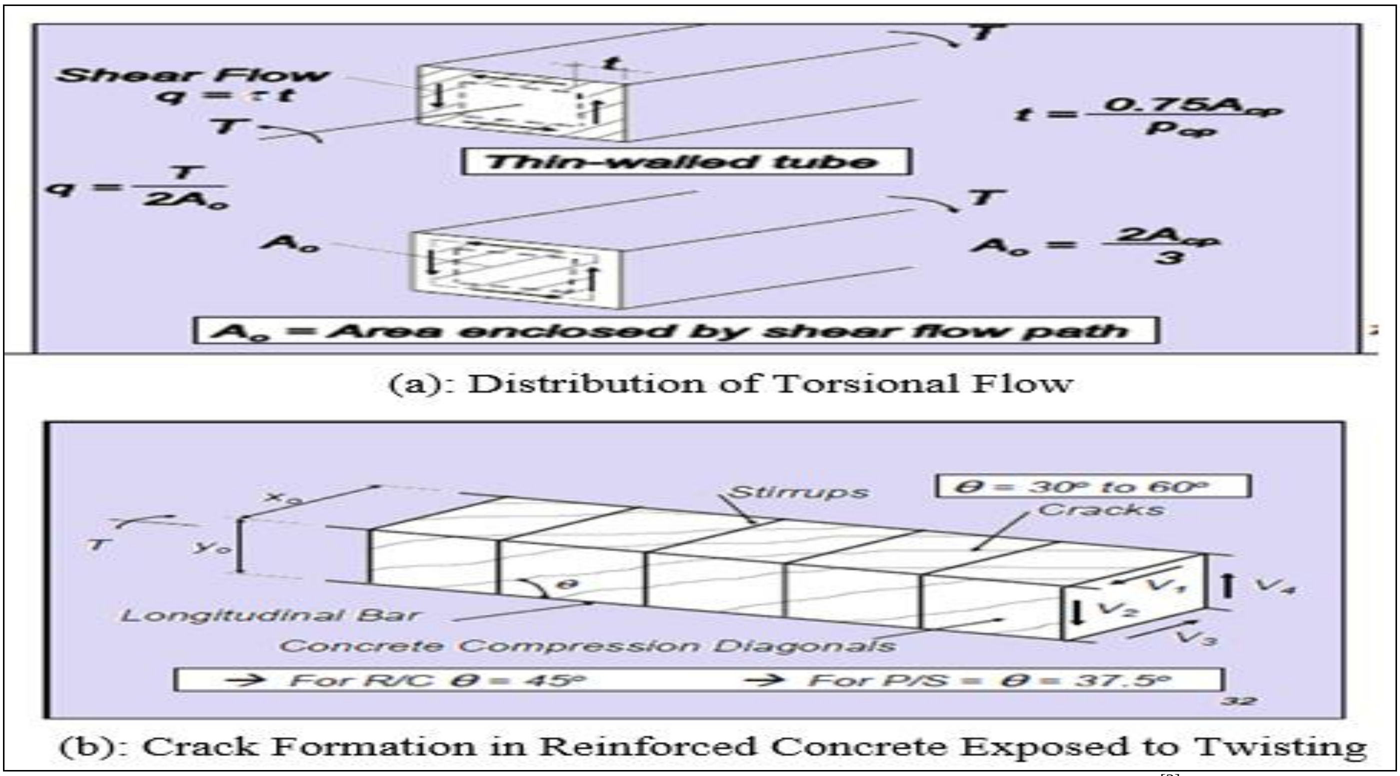

Fig 2: Space Truss Analogy: (a): Distribution of Torsional Flow, (b) Cracks Generation.[3]

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II. TORSION THEORIES AND LITERATURE SURVEY

Most of the past studies and theories were focused on the elastic analysis of spandrel-floor beams under static loads only. The basic torsion theories were presented by Navier,

Navier[1] established a theory for the torsion of homogeneous elastic members with circular cross-sections. Saint-Venant later advanced this work by deriving an elastic solution for the torsion of rectangular cross-section members, demonstrating that torsional stresses circulate in a circular pattern. He found that maximum shear stresses occur at the center of the longer side, concluding that a thin tube represents the most efficient cross-section for resisting torsion. In 1896, Bredt formulated a straightforward equation for thin tubes, which became a foundational element for modern theories regarding cracked reinforced concrete members subjected to Saint-Venant's torsion. His theory stated that the shear stress multiplied by wall thickness has a constant value around the perimeter and that this shear flow (q) is found by dividing the torsion (T) by twice the area enclosed by the shear flow bath (A_O). $q = \frac{T}{2AO}$

All the previous theories (theories of Navier, Saint-Venant and Bredt) are suitable to the reinforced concrete members before cracking.

In 1929, Rausch[2] proposed a three-dimensional space truss model to analyze torsion in reinforced concrete, expanding on Ritter's two-dimensional plane truss model for shear design. This model incorporates 45-degree diagonal concrete struts, longitudinal reinforcing bars, and stirrups, all connected by hinges at the joints. It posits that the torsional capacity of a rectangular section arises from the combined action of reinforcement and the surrounding concrete, with longitudinal and stirrup reinforcements resisting tensile stresses and concrete struts counteracting compressive forces. Torsional moments are transmitted through the concrete struts and reinforcing bars, with shear flow following the centerline of the stirrup reinforcement

Hsu [4], 1968, studied the behavior of reinforced concrete spandrel-floor beams experimentally and developed the skew bending theory. Collins and Lampert [5] concluded that the ratio of torsional to flexural stiffness will drop at cracking and that will cause redistribution of the torsion and flexural moments. So that the magnitude of compatibility torsion is over estimated if gross stiffness is used. Hsu and Burton[6], 1974, tested ten specimens under two type of loading, it was concluded that, using the limit design concept is both feasible and desirable to obtain the torsional stress. Minimum steel ratio in the floor beam at the joint may be taken as 0.45% for crack control. Mohammed Ali[7] tested eighteen assemblies of spandrel-floor beams and categorized into five distinct groups based on various parameters. The results indicated that the location of the torsional plastic hinge is significantly influenced by the amount of steel reinforcement incorporated into the spandrel beam. Furthermore, the longitudinal reinforcement within the spandrel beam demonstrated minimal effectiveness in enhancing torsional resistance. As a result, it may be concluded that the inclusion of longitudinal steel reinforcement for the purpose of resisting torsion in spandrel beams is unwarranted. Easa[8] tested seventeen reinforced concrete hollow spandrel beams under two types of loading. It was concluded that, the additional loading case has no effects on the overall behavior since it reinforced probably. Transverse steel has no influence on the beams prior to cracking. In 2006 Hago et al.[9] applied direct design method DDM for proportioning the reinforcement required to resist a combination of torsion, bending and shear on reinforced concrete members. They concluded that DDM yield more saving in steel than that provided by present codes BS8110 and ACI318. To meet durability requirements, the thickness of sandwich plates should be no less than twice the thickness of the cover

III. GENERAL DESCRIPTIONS AND ANSYS14.0 APPLICATION

Data were selected from spandrel-floor beams for previous experimental works [8, 10, 11 and 12]. The members under investigation exhibited variations in size, reinforcement details, material properties, types of spandrel sections (solid or hollow), design criteria, and loading conditions. All specimens were subjected solely to static loads. T-shaped test specimens, as illustrated in Fig. (3.7-c), were utilized and were cut at the inflection points. (3.7-a and -b), forming a spandrel-floor beam assembly. The cut-off sections were simulated by an appropriate hinge and restraint at testing. The ends of the spandrel beams were subjected to torsional fixity. Although this condition of complete torsional fixity does not precisely represent the behavior of the framed structure, it was implemented for testing purposes to significantly simplify the analysis and testing procedures.

The torsional fixity of the spandrel beams was attained by attaching an arm to the ends of the beams using a plate and bolts, as depicted in Fig. (3.7-d). The actual length of the test specimens was increased by values not more than (300mm) to provide an adequate support at each of the three cut-off points [9, 10, 11, 12 and 13]. The longitudinal bars of the floor beams were placed on top of the longitudinal bars of the spandrel beam at the joint. This detailing of the reinforcement bars was found to be quite efficient in transferring loads from the floor beam into the spandrel beam [8, 10, 11 and 12].

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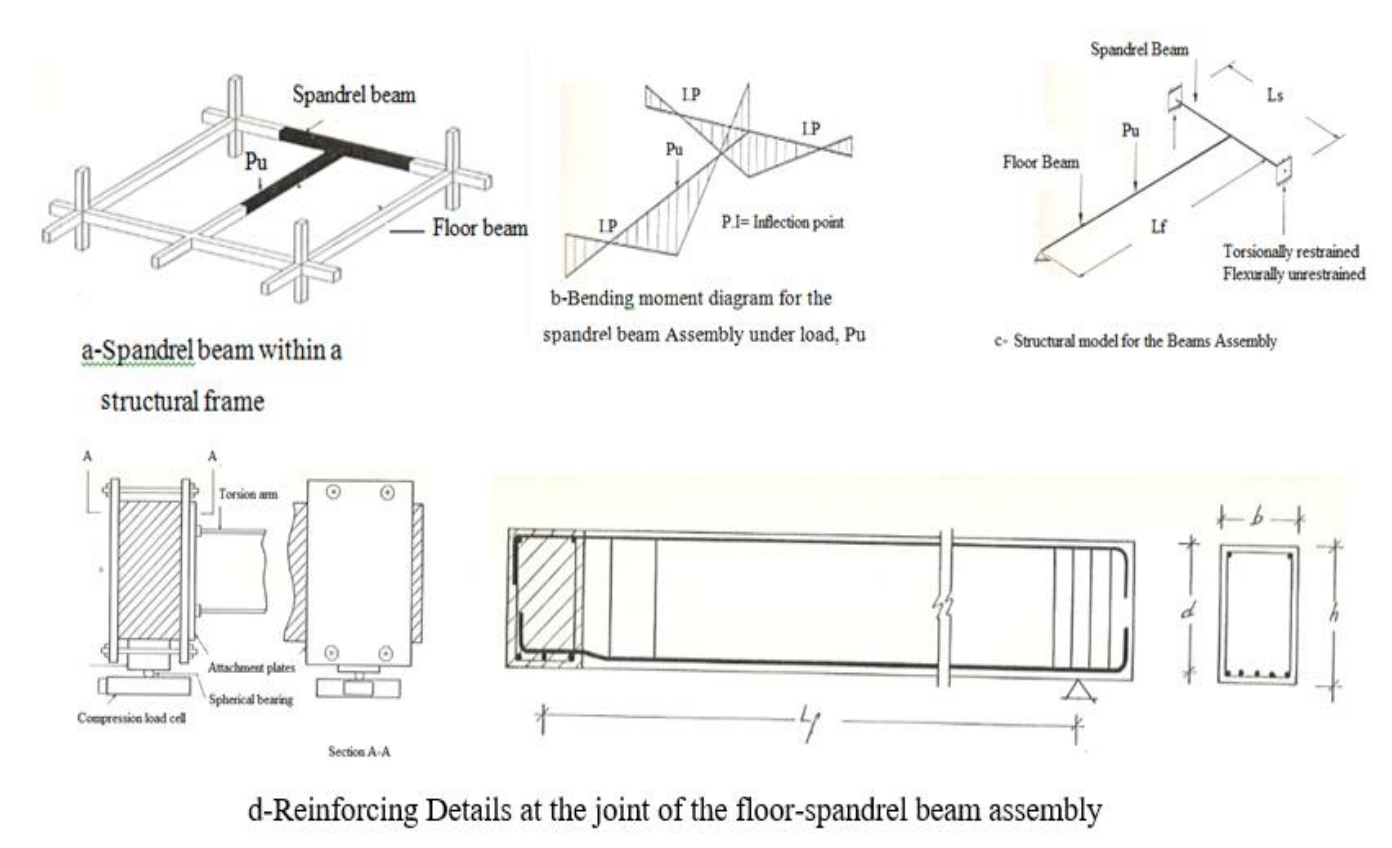

Fig 3: Typical Details for the Tested Spandrel-Floor Beams Assembly [11].

Fig. (3.8-e) presents a typical layout of the reinforcement employed in the test specimen. [13]. The load was systematically applied and incrementally increased to a predetermined value, which was subsequently maintained for a specified duration. Concurrently, the hydraulic jacks positioned beneath the torsion arms were engaged to ensure the preservation of their initial configurations. Following this stabilization phase, all relevant measurements were recorded. The loading was then raised to the next designated stage at the same rate, with the procedures previously described being reiterated. The assembly was deemed to have reached failure when a marked decline in the applied load was observed, accompanied by significant deflection or torsion. In the computational model, specific properties were utilized to accurately simulate the steel reinforcement, including longitudinal bars and stirrups, of the spandrel-floor beams. The steel arms and plates were represented using Solid 185 elements characterized by linear material properties. The specification, material properties and analysis results are shown in table (1).

The tested beams were modeled using ANSYS 14.0 (Structural/LS-DYNA). To simulate the concrete of the floor and spandrel beams, the Solid65 element was utilized, incorporating linear and multi-linear isotropic material properties, as well as capabilities for crushing and cracking. Additionally, the Link180 element was employed in the analysis.

Table 1(A): Dimensions, Properties of Concrete, and Analytical Results for A-Spandrel Floor Beams

Investig-ator	Spec GR-	**Spandrel beam**			**Floor beam**			f'_c MPa	Ec GPa	**Ultimate load**		**Pan / Pex**	**Ultimate Torque**		**Tans / Texp**	**Angule of Twist (Rad/m) x10^{-3}**		**Ѳan / Ѳex**
		Ls M	Bs Mm	Hs Mm	Lf M	Bf Mm	Hf mm			Pex	Pan		Tex	Tan		**Ѳe**	**Ѳa**	
Jawad [10]	B1							32.8	30.6	82.8	85.0	1.02	2.65	2.78	1.04	23	24	1.03
	C1	1.2	120	300	1.6	120	180	30.6	29.8	74.4	75.0	1.00	3.97	3.25	0.82	28	30	1.07
Muherdeen ; [11]	A2	1.5	120	300	1.5	120	300	30.3	29.6	95.2	74.0	0.78	1.80	1.7	0.94	10	7.3	0.72
	D1	1.5	120	300	1.5	120	300	20.0	25.8	81.4	80.0	0.99	1.61	1.80	1.10	9.7	8.37	0.86
Easa[8]	A2	1.5	200	300	1.7	150	300	26.9	26.2	110	110	1.00	7.58	6.30	0.83	34	25.0	0.78
	B2	1.5	200	300	1.7	150	300	27.0	27.2	105	110	1.05	3.60	3.35	0.93	33	27.0	0.84
Abul Mansur and Rangan	SA3	3.0	180	300	3.0	180	300	40.2	4.0	138	138	1.00	6.6	5.4	0.82	13.5	11.2	0.83

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Table 1(B): Details and Properties of Steel.

Spec. GR.	**Reinforcement of Spandrel Beam**			**Reinforcement of Floor Beam**			f_y **(Mpa)**	Es **(Gpa)**
	(+ve)	**(-ve)**	**Stirrups**	**(+ve)**	**(-ve)**	**Stirrups**		
B1[10]	2 Φ10	2 Φ 10	Φ5.5@90 mm	2 Φ 18	2 Φ 10	Φ5.5@75mm	Φ18 f_y =486.2 Φ16 f_y =478.4 Φ12 f_y =473.6 Φ10 f_y =470.3 Φ5.5 f_y =350.3	Φ18 Es=2.19 Φ16 Es=2.06 Φ12 Es=2.47 Φ10 Es=2.00 Φ5.5 Es=1.97
C1[10]	2 Φ 10	2 Φ 10	Φ5.5@140 mm	2 Φ 16	2 Φ 10	Φ5.5@75 mm		
GRA2[11]	2 Φ 10	2 Φ 10	0	2 Φ 12	2 Φ 10	Φ5.7@90 mm	Φ12 f_y =560.8 Φ10 f_y =559.3 Φ5.7 f_y =250.0	Φ12 Es=1.98 Φ10 Es=2.00 Φ5.7 Es=1.96
GRD1[11]	2 Φ 10	2 Φ 10	0	2 Φ 12	2 Φ 10	Φ5.7@80 mm		
GRA2[8]	2 Φ10	2 Φ 10	Φ7@90mm	2 Φ 12	2 Φ 10	Φ7@135mm	Φ12 f_y =560.0 Φ10 f_y =561.0 Φ7 f_y =240.0	Φ12 Es=2.01 Φ10 Es=1.98 Φ5.7 Es=1.92
GRB2[8]	2 Φ10	2 Φ 10	0	2 Φ 12	2 Φ 10	Φ7@135mm		

A. Effects of Main Steel Reinforcement of the floor Beams on The Analysis Results for Different (L_f/L_s) Ratios

The Floor beam length to spandrel beam length ratios (L_f/L_s) have significant effects on the analysis results[13]. The effects of positive steel reinforcement of the floor beams on the analysis results for five ratios of 0.5, 1.0, 1.5, 2.0, 2.5 of L_f/L_s was studied using seven cases of different size of steel bars for the main reinforcement of the floor beams. The steel ratios of these bars were selected within the minimum and the maximum limitation presented in the ACI Code [14].

As shown in table (2) and Fig. (4), the ultimate loads, the max. vertical deflection and the ultimate torque were affected by the main steel reinforcement of the floor, especially after cracking occurred, since a redistribution of internal stresses occurred and some of the transforming torque will return back to the floor beams which will be supported by the longitudinal main reinforcement of the floor beams. Therefore, sufficient reinforcement should be provided to ensure the design requirements.

Many notations were recorded and some conclusions could be summarized as below:

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Table 2: Reinforcement Effects of Main Reinforcement of the Floor Beams on the Analysis Results for Different L_f/L_s Ratios

Steel Bars	Lf/ ls	Ultimate Laod(kN)					Max.Deflection(mm)					Ultimate Torque(kN.m)				
		0.75	**1.0**	**1.5**	**2.0**	**2.5**	**0.75**	**1.0**	**1.5**	**2.0**	**2.5**	**0.75**	**1.0**	**1.5**	**2.0**	**2.5**
2 R 6		23	40	33	28	14	8.5	10	15	25	16	1.5	2.58	3.0	3.2	3.1
2 R 8		33	56	45	37	22	7.46	9.5	16.5	20	12	1.51	2.37	3.10	3.3	3.6
2 R10		31	74	57	49	21	4.0	6.9	11.0	18.0	8.8	1.54	1.89	2.67	3.0	2.19
2 R12		36	96	73	58	9	3.8	5.3	11.5	10.0	2.0	2.28	1.66	2.29	2.7	1.6
2 R14		37	37	95	86	78	3.2	3.8	10.6	21.0	3.0	4.4	1.35	2.2	2.7	2.1
2 R16		85	120	100	90	17	4.5	5.5	7.8	6.0	3.0	5.8	1.2	2.1	2.2	1.5
2 R18		66	170	100	87	11	5.1	6.4	7.35	8.5	1.1	5.9	0.55	2.1	2.0	2.2

- Ultimate load carrying capacity of the spandrel-floor beams assembly, in which the min. ratios of main steel reinforcement were provided in the floor beams, can be increased to about four times by reinforcing the floor beam with maximum steel ratios without changing the cross-sectional area of the spandrel-floor beams assembly. However this will be not economic in case of low concentration of external forces.
- Transforming torque was also affected by steel ratios, since high transforming torque can be noticed in case of high steel ratios.
- Max. vertical deflection can be reduced to about five times by increasing the steel reinforcement of the floor beams to the max. steel ratios.
- At ratio (L_f/L_s) equal to about 1.0, max. ultimate load can be carried by the floor-spandrel beams assembly with less vertical deflections at all loads level. This ratio can be considered as the optimize ratio.
- Selection of the steel ratios of the positive longitudinal reinforcement of the floor beams has significant effects on the analysis results and should be selected according to the design requirement and the economic considerations.

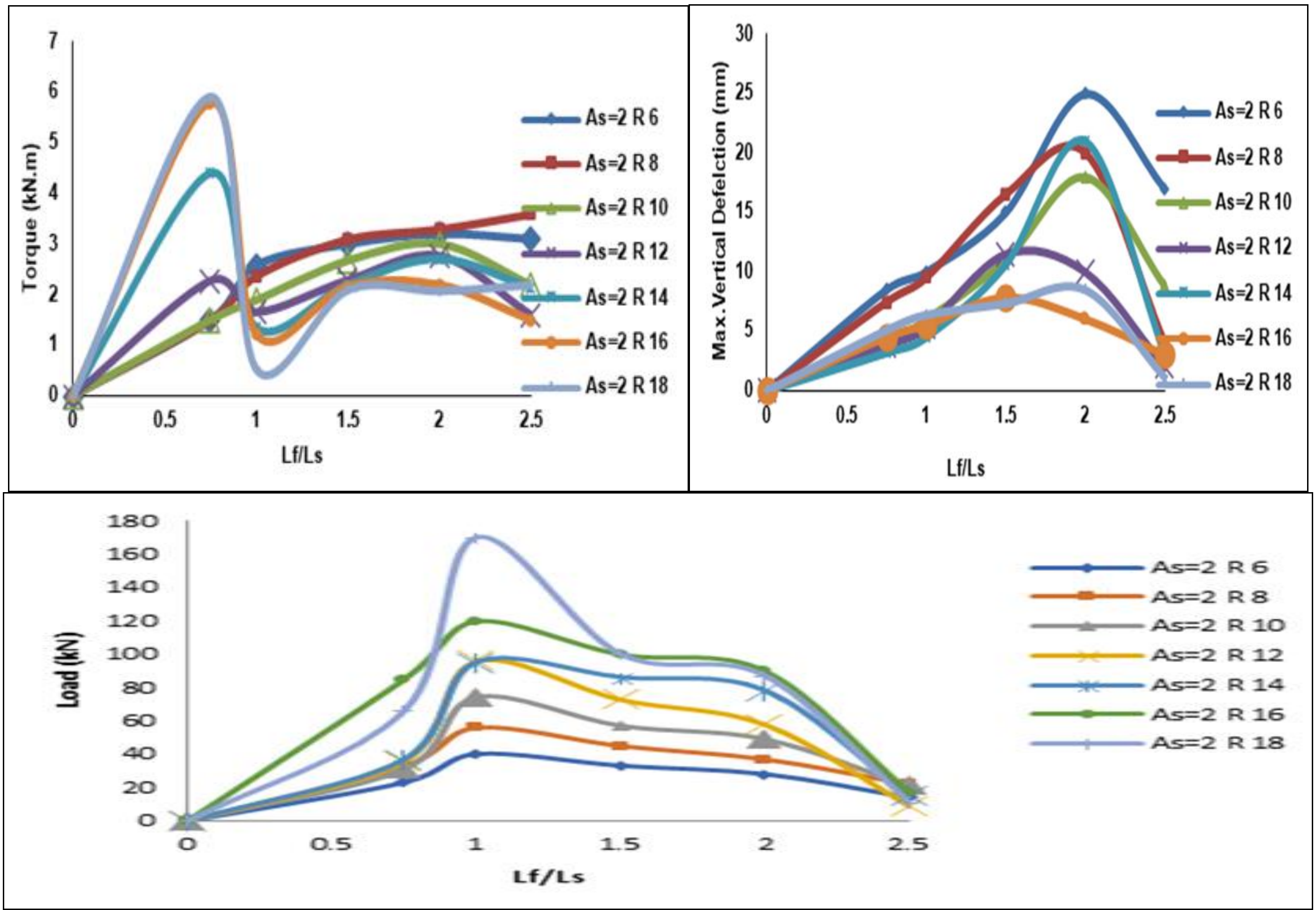

Fig 4: Relation between the Ultimate Load, Max. Deflection and Ultimate Torque with L_f/Ls Ratios for Different Steel Reinforcement of the Floor Beams

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➢ *Many Notations were Recorded and Some Conclusions could be Summarized as Below:*

- Ultimate load carrying capacity of the spandrel-floor beams assembly, in which the min. ratios of main steel reinforcement were provided in the floor beams, can be increased to about four times by reinforcing the floor beam with maximum steel ratios without changing the cross-sectional area of the spandrel-floor beams assembly. However this will be not economic in case of low concentration of external forces.
- Transforming torque was also affected by steel ratios, since high transforming torque can be noticed in case of high steel ratios.
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- Selection of the steel ratios of the positive longitudinal reinforcement of the floor beams has significant effects on the analysis results and should be selected according to the design requirement and the economic considerations.

B. Effects of Main Steel Reinforcement of the floor Beams on the Analysis Results for Different (h_f/h_s) Ratios

In order to study the effect of steel reinforcement of the floor beams on the analysis results of different floor to spandrel depth ratios (hf/hs), six cases which included different sizes of reinforcement bars, were investigated. The steel ratios of these reinforcement bars were within the limitation presented by the ACI Code[14].

Table 3: Reinforcement Effects of Main Reinforcement of the Floor Beams on the Analysis Results for Different h_f/h_s Ratios

Steel Bars		**Ultimate Load (kN)**				**Max. Deflection (mm)**				**Ultimate Torque (kN.m)**			
	h_f/h_s	**0.5**	**0.6**	**0.75**	**1.0**	**0.5**	**0.6**	**0.75**	**1.0**	**0.5**	**0.6**	**0.75**	**1.0**
2 R 6		12	24	30	40	6	8.0	12	7.3	0.56	0.56	3.5	1.0
2 R 8		24	55	47	63	53	7.3	9.5	5.4	0.5	0.50	3.4	1.6
2 R10		32	45	60	83	5	7.0	5.5	4.5	0.4	0.4	3.26	1.2
2 R12		30	52	72	100	4	5.85	4.0	3.0	0.38	0.38	3.15	0.9
2 R14		40	62	84	130	5.3	5.5	4.1	2.1	0.95	095	3.46	1.0
2 R16		59	69	75	97	4.1	4.67	3.6	1.5	1.0	10	3.21	0.95

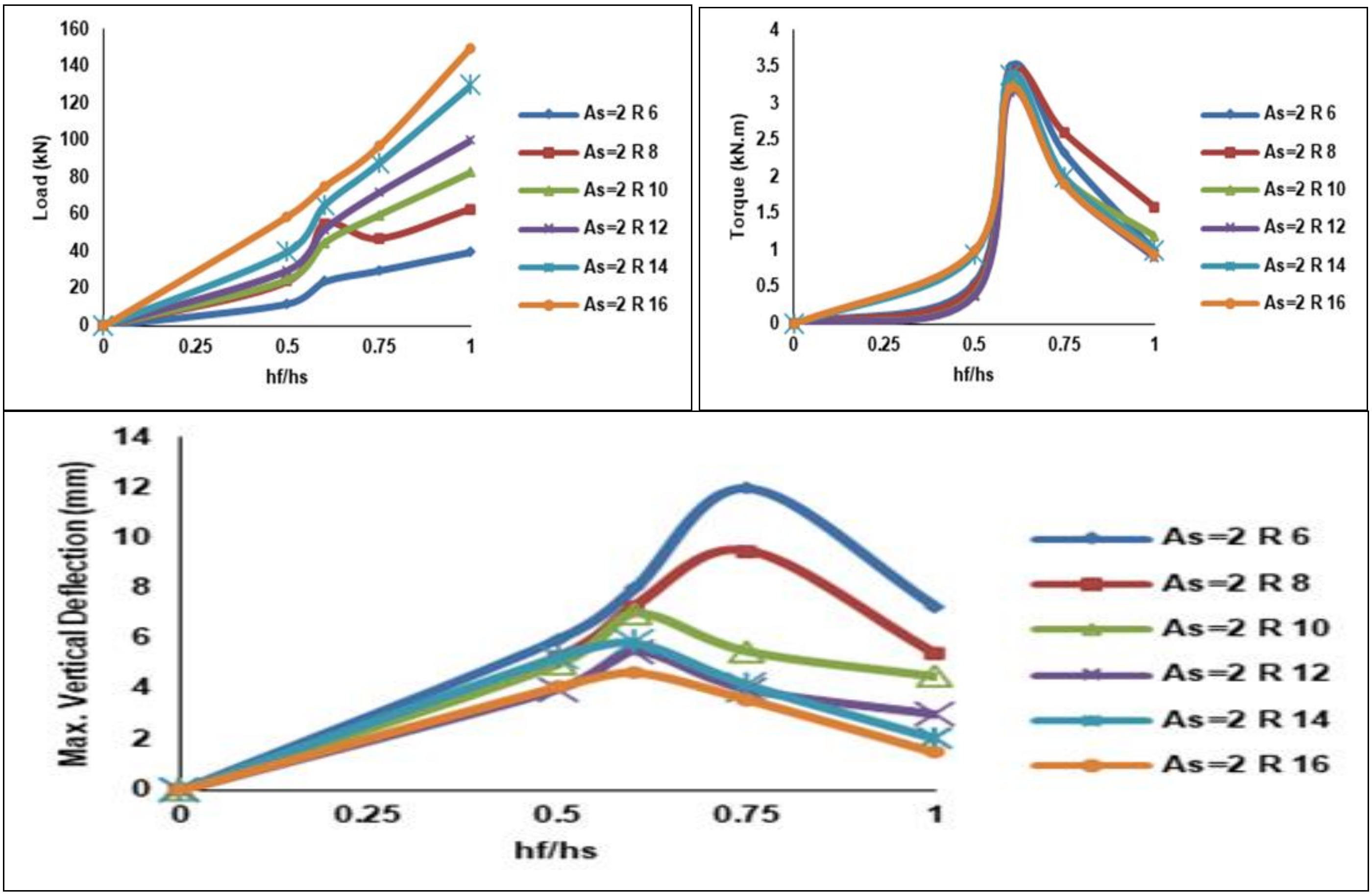

Fig 5: Reinforcement Effects on the Analysis Results for Different hf/hs Ratios

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➢ *The Analysis Results are Presented in Table (3) and Fig. (5), it can be Noticed that:*

- Positive steel reinforcement of the floor beams have significant effects on the analysis results. The analysis results were also affected by the h_f/h_s ratios.
- Max. ultimate loads can be obtained at the max. steel ratios.
- Vertical deflection can be decreased to about half its values by using max. steel ratios without changing the cross-sectional area and/or the material properties of the floor and the spandrel beams. This solution will be benefit in case of high deflections were exceeded the limitation that may cause a serious damage.
- Max. transforming torque for all cases of steel ratios can be noticed at h_f/h_s ratios equal to about 0.6. Those torques will decease as the h_f/h_s increase.
- The general behaviour of the spandrel-floor beams of different steel ratios have the same response to the h_f/h_s ratios.

IV. CONCLUSION

➢ *From the Present Study it can be Concluded that:*

- The behaviour of the spandrel-floor beams are widely effected by the positive reinforcement of the floor beam properties, especially after cracking occurred, since a redistribution of internal stresses occurred and some of the transforming torque will return back to the floor beams which will be supported by the longitudinal main reinforcement of the floor beams. This phenomenon can be involve to resist higher loads with less deflection without changing the concrete sections of the spandrel and or floor beam taking into account the design requirement and the economic considerations.
- At ratio (L_f/L_s) equal to about 1.0, max. ultimate load can be carried by the floor-spandrel beams assembly with less vertical deflections at all loads.
- Max. transforming torque for all cases of steel ratios can be noticed at h_f/h_s ratios equal to about 0.6.
- Transforming torque was also affected by steel ratios, since high transforming torque can be noticed in case of high steel ratios.

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