Experimental Investigation into the Effects of Construction Errors in Reinforced Concrete Beams

Afunanya, J.E, Williams, F.N and Tok, T.Y

Department of Building, University of Jos Nigeria
Correspondence email: jonasafunanya@yahoo.com

Abstract - This research investigated through experimental procedure the effects of construction errors in flexural and shear reinforcement of reinforced concrete (RC) beams. This was achieved by casting and testing fifteen RC beam specimens (1000 × 120 × 150mm) under the four point bending test in Heavy Structures Laboratory at Swansea University UK. The test variable is the arrangement of tensile steel reinforcements and transverse shear links. Beam specimens were categorized into two series according to their designed modes of failure i.e. flexural and shear. Flexural specimens were significantly reinforced in shear, to ensure flexural failure whist shear specimens were significantly reinforced in flexure to ensure shear failure. For each specimen series, three cast beam specimens served as the control whilst nine others (three for each construction error investigated) were cast with a construction error in either tensile steel reinforcement or transverse shear links. Analysis and discussion of results is based on the failure modes, ultimate loads sustained and load-deflection behaviour of beam specimens. Test results indicate that a reduction in the effective depth of specimens in the flexural series led to an 8.14% and 28.6% decrease in strength and ductility of beam specimens. For the shear series; the removal of a transverse shear link and the inclination of transverse shear links at 60° resulted in 14.1% and 10.6% decrease in strength and 12.8% and 20.9% decrease in ductility respectively.

Keywords: construction errors; flexural failure; shear failure; tensile steel reinforcement; transverse shear reinforcement

1.0 Introduction

Structural failure and collapse as a result of construction errors continue to plague the construction industry with notable consequences even though they can be prevented [1], [2], [3]. Studying and understanding the effects of such errors in relation to the on-site construction process cannot be overemphasised as it enables construction professionals to design and construct safer structures, ensure adequate quality control and inspection. Construction errors are departures from an intended action or an unexpected event that occurred by chance that arise either consciously or unconsciously in the form of mistakes, omissions, non-adherence and lapses which remain unnoticed and occur because of physiological and psychological shortcomings of humans [4], [5].

Construction errors resulting in failure of structures has been attributed to human errors that exceed construction specification [6]. Also in agreement is [7], who asserts that human error predominates in the failure of structures in the built environment whilst [8] noted that though the likelihood of structures to fail at the construction phase is higher, not all cases of failure in the construction phase are due to construction errors. Studies by [5] indicate that 80-90% of failure of structures is as a result of design and construction errors. According to Eldukair and Ayyub (1991) in [2], 56% of errors occur during the construction phase whilst studies by [9] on 225 cases of building failures in the United States from 1989 to 2000 indicates that failures during the construction phase occur four times more than during occupancy.

Related literature [10], [5], [11] suggests that many cases of structural failures often cannot be attributed to a single error but rather as a result of interdependently cumulative errors leading up to failure. Construction errors could initiate in a structural member, resulting in localised failure. If the structure is well designed failure will not occur, however, many cases of failure suggest that the non-existence of an alternate load path for redistribution of load often lead to more extensive failure or collapse. According to [11] in the investigation of failure of 127 structures, mostly in Scandinavia, a greater proportion of beams in particular failed as compared to other structural members and 45% of failures were as a result of design errors whilst 25% were as result of construction errors. A Study by [12] on 1,029 cases of building failure due to snow loads in the US between 1989 and 2009 and international failures between 1979 and 2009 suggests that the principal causes of collapse of concrete structures were construction errors, design errors and inadequate maintenance.

A study on building failures in the Penang area of Malaysia from the perspective of construction professionals suggests that the use of substandard materials and construction errors were the governing factors that triggered the failure of buildings [13]. A simulation experiment designed and conducted by [2] to determine the effects of experience, education and interruptions on the total inspection time and error detection rate of inspectors for a RC slab construction task indicates that the highest number of inspection errors was found in reinforcement arrangement and that neither education nor experience alone produced an acceptable inspection result. Similarly, [14] conducted a human reliability analysis incorporating the influence of construction errors and inspections to determine the relationship between construction quality control, partial safety factors and structural reliability of a RC beam and opined that structural reliability with and without inspections are relatively insensitive to variations in safety factors and increasing partial safety factors is not a viable alternative to the omission of inspections.

Table 1 Construction errors investigated in this research

Specimens series	Specimens notation	Construction errors
Flexural failure	BFE1	Tensile steel reinforcement placed at the wrong depth
Shear failure	BSE1	Incorrectly spaced shear links
	BSE2	Shear links inclined at an impermissible angle 60°

The research presented in this paper seeks to determine through experimental procedure, variation(s) to the original design as a result of three construction errors in the arrangement of tensile and shear reinforcements of a RC beam. The construction errors investigated is described in Table 1 and depict typical human errors during the construction phase of structures. The flexural error i.e. BFE1 involve a reduction in the effective depth of the RC beam. In the shear series, BSE1 involve the incorrect spacing of shear reinforcements at 150mm c/c against 130mm c/c resulting in the omission of shear link in the beam span whilst BSE2 involve the inclination of shear reinforcements at 60° as against a vertical alignment of 90°. These construction errors typify common lapses either consciously or unconsciously in the construction process which could be as a result of poor workmanship, cost cutting tendencies and ignorance as classified by Reason (1990) in **[2]** as skill based error and lapses, rule based errors and knowledge based errors.

2.0 Experimental Programme

This section describes the experimental programme adopted in this research.

Table 2 Specimens properties

Specimen series	Notation	Qty. cast	d (mm)	a/d (mm)	Longitudinal steel reinforcement (mm)	As (mm2)	Shear link (mm)	Spacing (mm)
Flexural failure	BFC (control)	3.00	100.00	4.00	H10	157.00	H8	80.00
	BFE1	3.00	112.00	3.50	H10	157.00	H8	80.00
Shear failure	BSC (control)	3.00	109.00	3.60	H16	402.00	H8	130.00
	BSE1	3.00	109.00	3.60	H16	402.00	H8	150.00
	BSE2	3.00	109.00	3.60	H16	402.00	H8	130.00

Table 3 Concrete mix content

Compressive strength (MPa)	Water - Cement ratio	Mass (kg)			
		Water	Cement	Fine aggregate	Coarse aggregate
50	0.5	14.6	29.5	53.2	64.9

2.1 Specimen Details

To achieve the research objectives, fifteen simply supported reinforced concrete beams ($1000 \times 120 \times 150$mm) were fabricated and tested in the Heavy Structures Laboratory at Swansea University, UK. Specimens were categorised into two series; flexural and shear, depicting their designed modes of failure. Flexural specimens were significantly reinforced in shear to ensure flexural failure whilst shear specimens were significantly reinforced in flexure to ensure shear failure. The test variable investigated is the arrangement of tensile steel reinforcement and transverse shear links. Six specimens served as control (three for each failure type) that were designed, fabricated and cast as specified by Eurocode2 to fail either in flexure or shear. Nine other specimens described in Table 1 were fabricated and cast with a typical onsite construction error in either flexural or shear reinforcement.

Table 2 shows the properties of specimens, including the shear span to depth ratio (a/d), area of longitudinal steel reinforcement (A_s), diameter (ϕ) and effective depth (d) etc. Specimens are named according to the failure mode they depict and the number of errors investigated in each series. For example, specimen BSC implies beam shear control whilst specimen BFE1 implies beam flexural error one. The construction error investigated in the flexural series had a reduction in its effective depth from 112mm in the control to 105mm in BFE1. In the shear series, two errors were investigated; BSE1 had its entire transverse shear reinforcement incorrectly spaced at 150mm c/c as against 130mm c/c in the control whilst BSE2 had same number of shear links with the control, but were all inclined at 60°.

2.2 Specimen Materials

Beam specimens consist primarily of concrete and steel reinforcement. A high grade concrete with a compressive strength of 50MPa was utilized and kept constant for all specimens. The concrete contained coarse aggregates with a maximum size of 20mm, fine aggregates, ordinary Portland cement and fresh tap water. Batching of concrete was by weight and prior to the determination of the concrete mix ratio; particle size analysis and moisture content tests conforming to [15] were carried out on aggregates. The average moisture content was computed and necessary adjustments made to concrete mix ratio as the concrete mix design presumes that aggregate samples are completely dry. Table 3 shows the concrete mix content used for casting BFC. Specimens were cast in five batches, each batch producing three geometrically identical beam and cube samples. Curing was for 28days after which testing for properties of hardened concrete were conducted. Each beam specimen contains 2ϕH16 and 2ϕH10 longitudinal tensile steel reinforcement for shear and flexural specimen series respectively. Steel reinforcement cages were fabricated according to design specification using steel wires; 25mm concrete spacers were attached to the shear links at appropriate locations using steel wires to provide adequate cover to the beam specimens.

2.3 Test Set-up

Flexural strength test was conducted on beam specimens in accordance to [16]. The major components of the test facility include; the load controlled actuator, data acquisition system, two supporting rollers and two upper rollers carried by the loading frame. Symmetric concentrated loads were applied using a 1000kN Avery universal testing machine.

Fig 1: Specimens test set-up

All beam specimens were tested to failure under four point loading (two active and two passive) as shown in Fig. 1. The transfer of load from the loading frame to the beam specimens was through a proving ring of hydraulic jack placed on the top of specimens. The constant moment region was 205mm whilst the effective span was 900mm and was kept constant throughout the tests. The shear span was equal at adjacent ends of the beam specimens, creating a zero shear zone between the loading points.

2.4 Instrumentation and Data Acquisition

The instrumentation consists of a linear variable displacement transducer (LVDT), system 500 data logger, a computer system and 1mm thick spacer. The LVDT (as shown in fig.1) was mounted at mid-span of the bottom face of beam specimens to measure vertical deflection. 1mm thick spacer was placed on the tip of the LVDT to prevent damage to the LVDT and to ensure that deflection data are properly captured when cracks propagate. Load and deflection data were automatically recorded using the system 500 data logger and stored in the connected computer.

2.5 Loading Procedure

The loading procedure involved subjecting beam specimens to flexure until ultimate condition is attained. Ultimate condition is attained when a significant drop in peak load occurs. These was characterised by significant crack propagation for both specimens series and sudden failure peculiar to the shear series specimens. For the shear failure specimens (BSC, BSE1 and BSE2), the load was initially applied at a constant rate of stress between 0.04MPa/s to 0.06MPa/s. The loading rate was subsequently reduced by 25% when the applied load reached 5kN, and thereafter kept constant at this rate until failure. For the flexural failure specimens (BFC and BFE1), the load was applied monolithically from zero to failure at a constant rate of stress 0.04MPa/s.

3.0 Test Results and Discussion

The test results obtained from the experimental procedure is summarised in Table 5, S.D. and C.V. are standard deviation and coefficient of variation respectively. The effects of the arrangement of tensile steel reinforcement and transverse shear link in RC beams are analysed and discussed based on the ultimate loads sustained, failure modes and load – deflection behaviour.

Table 4 Statistical standards **[17]**

Level of control	S.D	C.V
Excellent	<3.00	-
Very good	3.00-3.50	<10.80
Good	3.50-4.00	-
Fair	4.00-5.50	10.20-17.20
Poor	>5.50	17.20-26.80

Table 5 Summary of test results

	Specimens series	Failure load (kN)	Average failure load (kN)	% difference	S.D.	C.V.	Max. mid-span deflection (mm)	Av. Max. mid –span deflection (mm)	Flexural strength (MPa)	Failure modes
Flexural series	BFC,A	49.86					7.54		16.60	Ten. failure
	BFC,B	50.95	50.50	0.00	0.57	0.01	5.13	6.89	17.00	Ten. failure
	BFC,C	50.69					7.99		16.90	Ten. failure
	BFE1,A	45.24					4.92		15.10	Ten. failure
	BFE1,B	48.63	46.39	-8.14	1.95	0.04	4.69	4.91	16.20	Ten. failure
	BFE1,C	45.28					5.13		15.10	Ten. failure
Shear series	BSC,A	70.45					4.45		23.50	Shear tension
	BSC,B	69.34	71.01	0.00	2.02	0.03	4.36	4.45	23.10	Shear tension
	BSC,C	73.25					4.54		24.10	Shear tension
	BSE1,A	58.29					3.77		19.40	Shear tension
	BSE1,B	63.83	61.00	-14.10	2.77	0.05	4.54	3.80	21.30	Shear tension
	BSE1,C	60.89					3.09		20.30	Shear tension
	BSE2,A	61.14					3.18		20.40	Shear tension
	BSE2,B	63.80	63.47	-10.62	2.19	0.03	4.00	3.45	21.30	Shear tension
	BSE2,C	65.48					3.18		21.80	Shear tension

3.1 Ultimate Load

Herein, the ultimate load refers to the average failure load sustained by specimens of same specimen type as shown in Table 5. BFC failed at an ultimate load and deflection of 50.5kN and 6.98mm respectively whilst BFE1 failed at an ultimate load and deflection of 46.4kN and 4.92mm respectively. This represents an 8.2% and 28.6% reduction in the strength and ductility respectively by BFE1 specimen when compared with the control specimen. In the shear series, BSC failed at an ultimate load and deflection of 71kN and 4.5mm respectively whilst BSE1 failed at an ultimate load and deflection of 61kN and 3.8mm. BSE2 failed at an ultimate load and deflection of 63.5kN and 3.45mm respectively. This indicates a 14.1% and 10.6% reduction in the ultimate load sustained by BSE1 and BSE2 respectively.

The above results suggests that beam specimens with incorrectly spaced transverse shear links (i.e. BSE1) is more hazardous and more likely to lead to failure as it recorded the most decrease in strength. However, it should be noted that beam specimens with transverse shear links inclined at an impermissible angle (i.e. BSE2) deflected the most with a 20.9% decrease in ductility. This marked decrease in ductility by BSE2 implies that it is more susceptible to sudden and brittle failure.

3.2 Failure Modes

Flexural series

Upon load application, concrete elements in the shear span attain the tensile strength of concrete before those in the flexural span. These results in the initiation of few shear cracks in the shear span approximately at 18kN. Shear cracks were not wide and did not grow significantly since the specimens were significantly reinforced in shear as shear reinforcement take up shear stresses. With further load increments, concrete elements in the flexural span are stressed until the tensile strength of concrete is attained, resulting in the appearance of vertical flexural cracks at the bottom of the flexural span. When the concrete cracks, stresses are transferred to the tensile steel reinforcement. Flexural tensile crack propagated in the constant bending moment region from the bottom to the loading points as shown in Fig. 2. Specimens in this series exhibited a more gradual ductile failure with considerable plastic deformation upon failure due to tension failure i.e., yielding of tensile steel reinforcement with significant crushing of concrete between load points.

Shear series

Flexural cracks perpendicular to the bottom edge of the specimens initiated at mid span, approximately at 45kN. With subsequent load increments, new cracks developed and the existing cracks widened insignificantly. As the load approached the maximum, diagonal tensile stresses reach the tensile strength of concrete and diagonal cracks develop. Thereafter, specimens failed in shear, failure took place only after the critical diagonal crack (Fig. 3) developed fully between the load and support regions. Shear tension failure was brittle and sudden with little or no warning before failure, characterised by small deflection and occurred only in one shear span upon yielding of transverse steel reinforcement. Except for BSC specimens, BSE1 and BSE2 exhibited little peeling of concrete at the outer face of load point of the failed shear span.

Fig 2: Flexural crack propagation of flexural series specimen

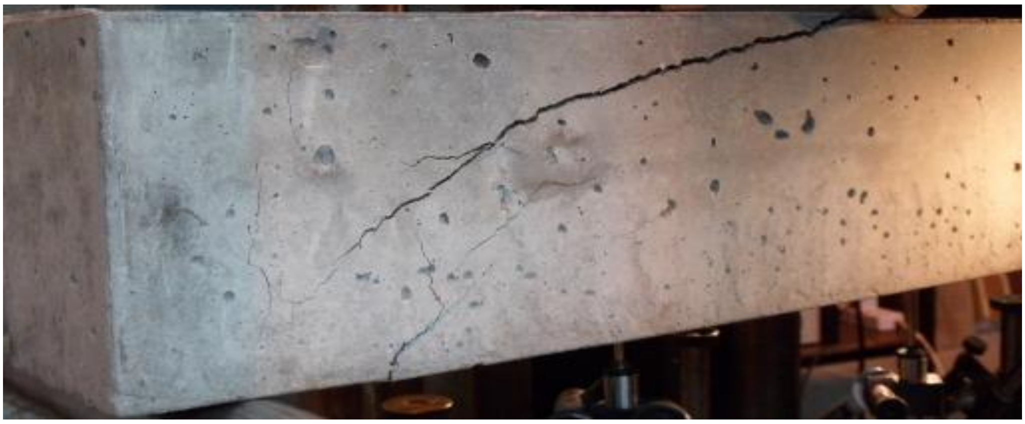

Fig 3: Critical diagonal crack propagation of shear series specimens

3.3 Load Deflection Relationship

Specimens in each series exhibited similar load deflection relationship; the load deflection plots (Figure 4-10) initially showed a linear-elastic behaviour until a relatively high level of stress is attained. Nonlinear behaviour initiates upon the attainment of this stress followed by plastic deformation of the beam specimens. It should be noted that specimens that attained the highest ultimate load for each specimen type was plotted together in fig. 6 & 10. The similarity in the shape of the load deflection curve for each specimen series and statistical standard based on Table 4 indicates an excellent level of control and consistency in the production of beam specimens.

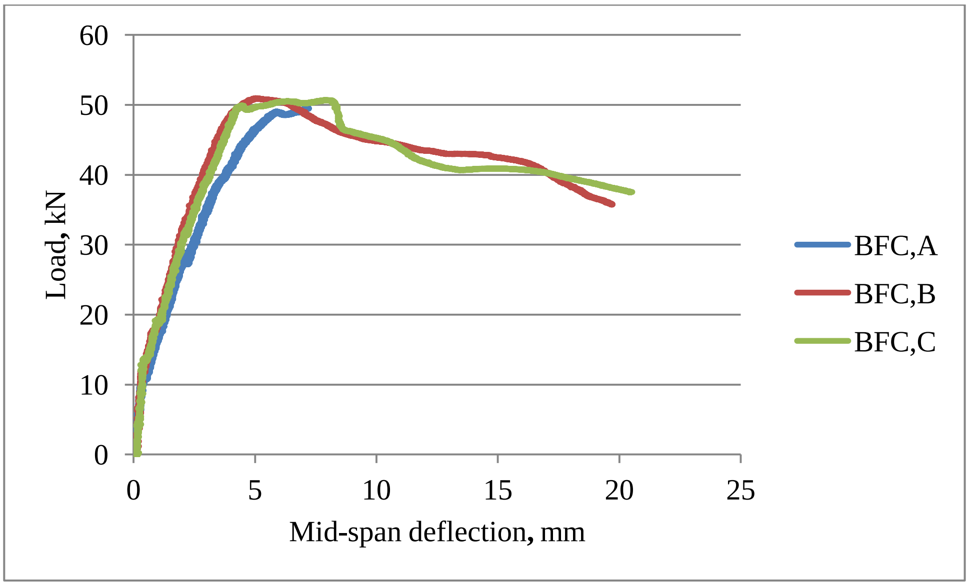

Fig 4: Load deflection plot of flexural control specimens (BFC)

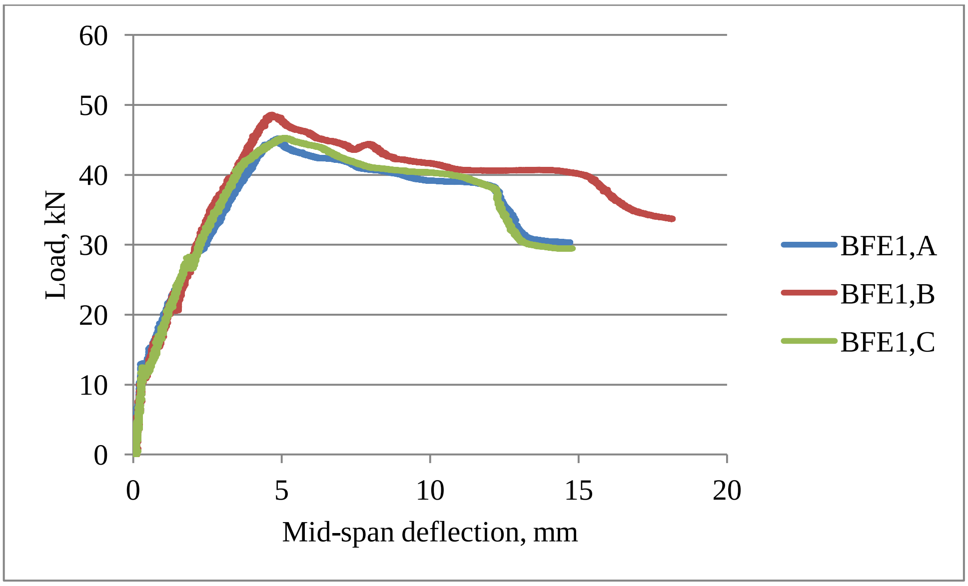

Fig 5: Load deflection plot of flexural error one specimens (BFE1)

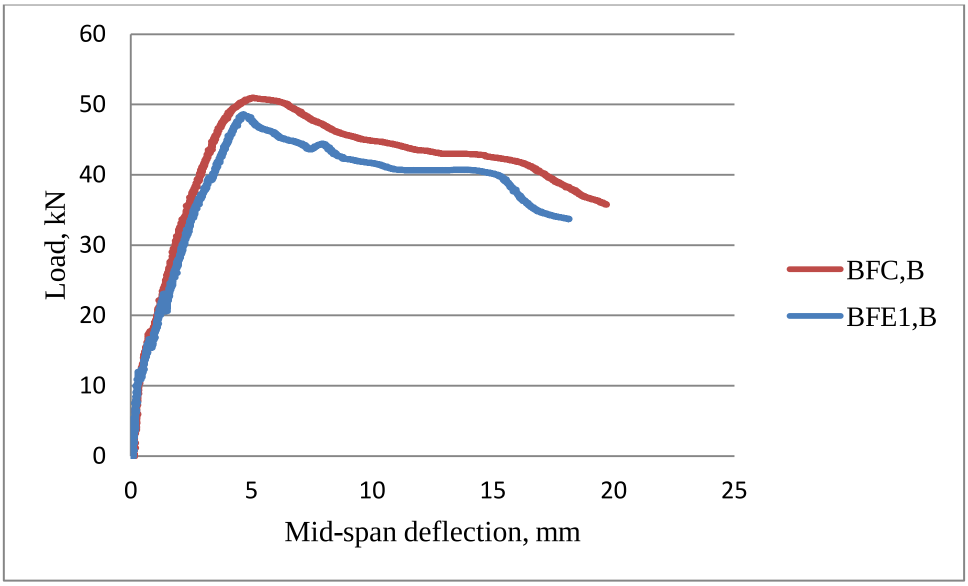

Fig 6: Load deflection plot of select flexural failure series specimens

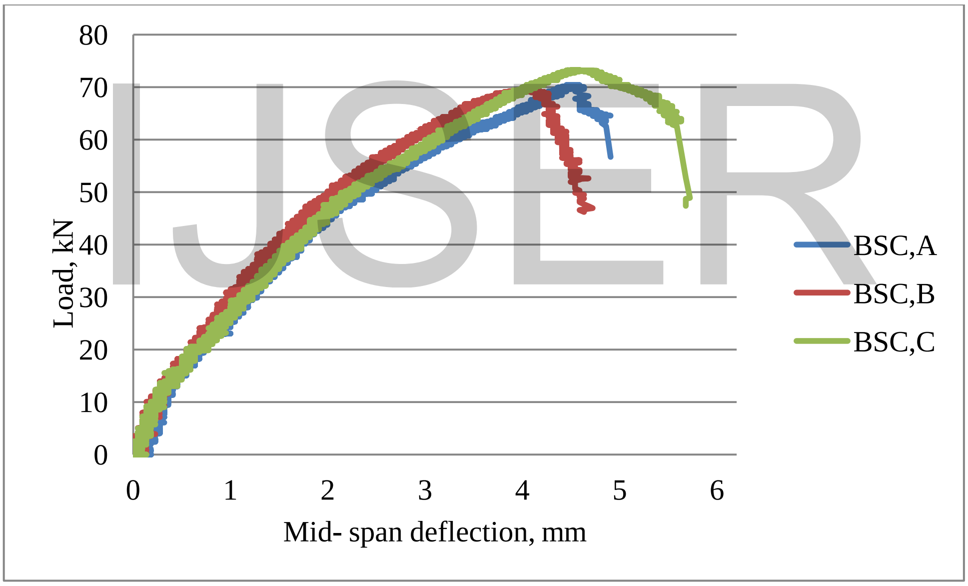

Fig 7: Load deflection plot of shear failure control specimens (BSC)

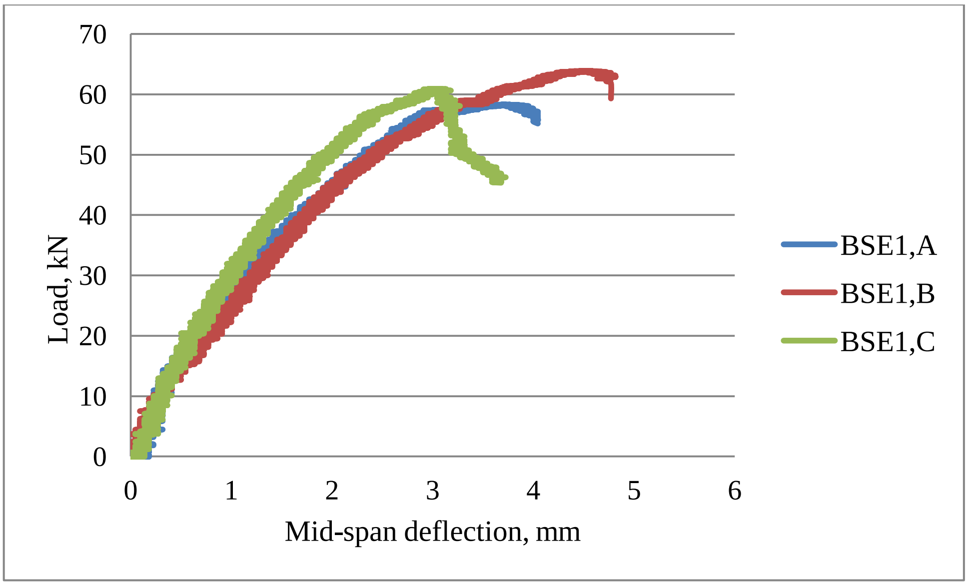

Fig 8: Load deflection plot of shear error one specimens (BSE1)

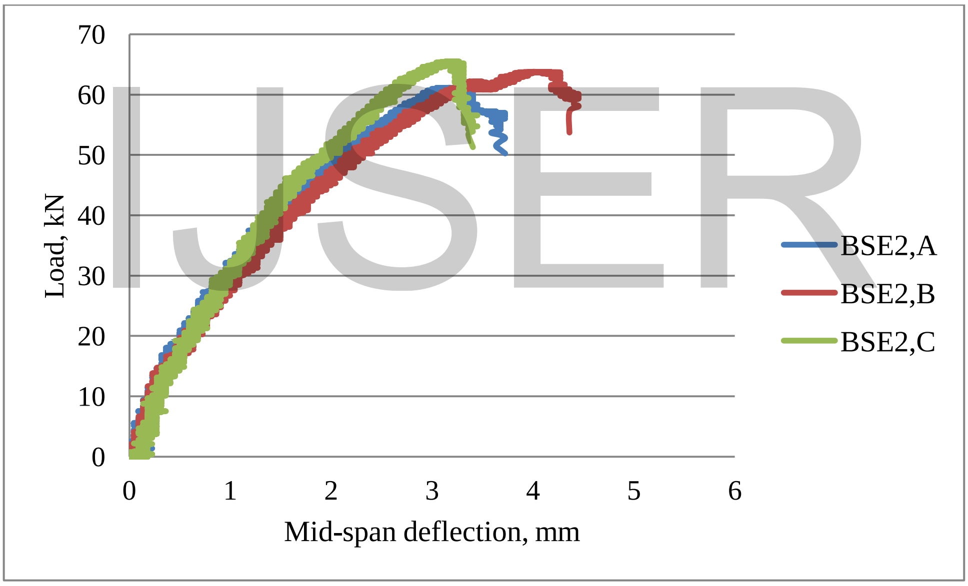

Fig 9: Load deflection plot of shear error two specimens (BSE2)

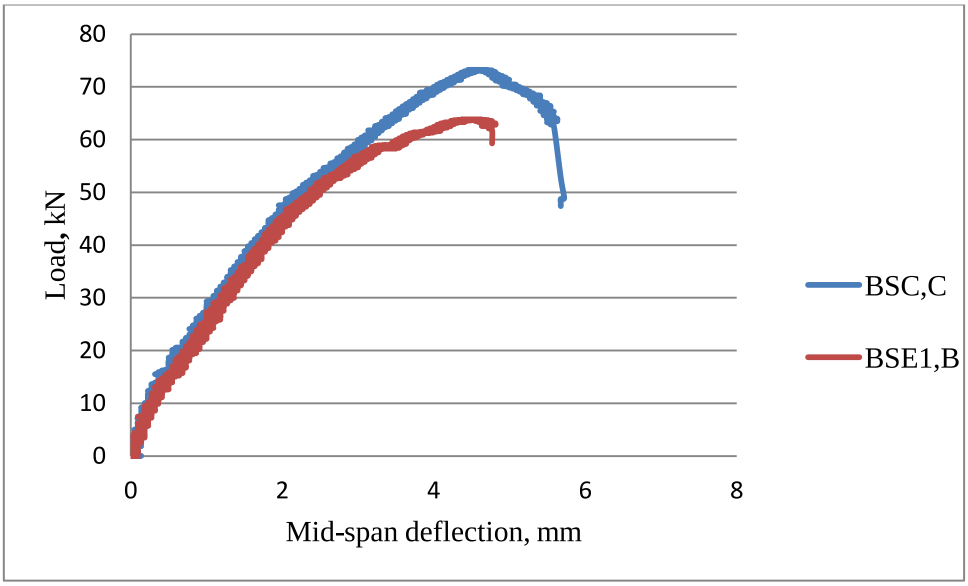

Fig 10: Load deflection plot of select shear failure series specimens

4.0 Conclusion

This research experimentally investigated the effects of construction errors in the arrangement of flexural and shear reinforcement of RC beams. From the above, it is sacrosanct for construction professionals involved in the insitu production of structures to employ adequate quality management and control procedures since the construction industry depends heavily on their inspections and supervision to achieve the required level of structural intergrity. Their ability to detect errors were they exist during the construction phase of structures would go a long way to forestall the occurence of failures and collapse as a result of construction errors.

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