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EXPERIMENTAL STUDY ON STRUCTURAL BEHAVIOR OF THIN WALL CONCRETE PANELS SUBJECTED TO AXIAL ECCENTRIC UNIFORMLY DISTRIBUTED LOADING

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Abstract: Due to the current popularity of reinforced concrete (RC) wall construction, and the new published of codes of concrete, RC walls have become just as an important structural elements as beam, slabs and columns. This paper presents an experimental study of structural behavior of thin concrete wall panels subjected to axial eccentric uniformly distributed loading with varying aspect ratio (AR=H/L) and concrete type (concrete strength (f'_c)). The experimental program included testing of six two-way thin concrete wall panels, fixed at all sides and applying the load axially with eccentricity equal to wall thickness/6).The results indicate that the load carrying capacity of the normal strength concrete (NSC) wall panels decreased with the increase in AR (H/L) from 1.25 to 2.00, the ultimate load reduced from 37.5% to 14.6 % when AR decreased from 2.00 to 1.25. For Reactive Powder Concrete (RPC), the ultimate load reduced from 38.7% to 16% when AR decreased from 2.00 to 1.25. The strength of the concrete wall increases with the increase in concrete strength (f'_c) from 33.5 MPa to 120.4 MPa , the increase is about (212.5, 207.3, 206.67) % for panels with H/L = (1.25, 1.50, 2.00) respectively. The lateral deflections of concrete wall panels depend on the aspect ratio (H/L) where, the increase in aspect ratio (H/L) from 1.25 to 2.00 of NSC panels causes increasing the lateral deflection of the concrete wall panels, while for Reactive Powder Concrete (RPC) wall panels the increase in aspect ratio (H/L) from 1.25 to 2.00 causes decreasing in the lateral deflection of the concrete wall panels. Also the lateral deflection depends on concrete type (concrete strength (f'_c)), when strength of the concrete wall panel increases from 33.5 to 120.4 MPa, the lateral deflection decreases.

Keywords: *Concrete Wall, Eccentric Load, Axial Load, Two-way Action, Normal Strength Concrete, Reactive Powder Concrete, Aspect Ratio.*

دراسة السلوك الإنشائي للألواح الجدارية الخرسانية النحيفة المعرضة الى تحميل محوري لامركزي منتشر

الخلاصة: نظرا للانتشار الأخير للبناء بالجدران الخرسانية المسلحة، والمدونات الجديدة الأميركية المنشورة لمعهد الخرسانة الأميركي ACI-Code، أصبحت الجدران الخرسانية عنصر انشائي هام مثل العتبات، والسقوف والأعمدة. هذا البحث يقدم دراسة للسلوك الانشائي للألواح الجدارية الخرسانية النحيفة المعرضة الى تحميل محوري لامركزي موزع بانتظام مع نسب مختلفة من نسبة الارتفاع على العرض(Aspect Ratio) ونوعية الخرسانة (مقاومة الخرسانة (f'_c)). البرنامج يتضمن فحص ستة نماذج من الألواح الجدارية (two-way action) الخرسانية النحيفة المثبتة بكل الجوانب وتسليط الحمل محوريا مع لا مركزية مساويه الى السمك مقسم على ستة (t/6). النتائج تشير إلى أن مقاومة الجدران الخرسانية (مقاومة الحمل العمودي) ذات المقاومة الاعتيادية تقل مع الزيادة في نسبة الارتفاع على العرض (H/L) من (1.25 الى 2.00)،)، الحمل الاقصى انخفض من 37.5٪ إلى 14.6٪ عندما انخفضت نسبة (H/L) من 2.00 الى 1.25. ولجدران خرسانة المساحيق الفعالة (RPC)، الحمل الاقصى انخفض من 38.7٪ إلى 16٪ عندما انخفضت نسبة (H/L) من 2.00

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الى 1.25. المقاومة للجدران الخرسانية تزداد مع الزيادة في مقاومة الخرسانة للانضغاط (f'_c) من 33.5 (MPa) إلى 120.4 (MPa). كانت الزيادة (212.5، 207.3، 206.67) ٪ للجدران مع H/L = (1.25، 1.50، 2.00) على التوالي. الازاحة الجانبية للألواح الجدارية الخرسانية يعتمد على نسبة الارتفاع على العرض (H/L) حيث أن الزيادة في نسبة الارتفاع على العرض (H/L) من 1.25 الى 2.00 لجدران المقاومة الاعتيادية (NSC) يسبب زيادة الازاحة الجانبية للألواح الجدارية الخرسانية، في حين أن جدران خرسانة المساحيق الفعالة (RPC) الزيادة في نسبة الارتفاع على العرض من 1.25 الى 2.00 يسبب تناقص في الازاحة الجانبية للألواح الجدارية الخرسانية. الازاحة الجانبية يعتمد أيضا على نوع الخرسانة (مقاومة الخرسانة للانضغاط (f'_c))، عندما تزداد مقاومة الخرسانة من (33.5 الى 120.4) (MPa)، يقلل من الازاحة الجانبية.

1. Introduction

Reinforced concrete walls, previously, were considered as non-load bearing and used for the protection from the outer environment with little consideration for the structural capacity of the wall as a structural element, mainly this is because of its very low working design stresses given in early versions of published concrete codes, and limited research was done on these elements. Load-bearing concrete walls resisting primarily (in-plane) vertical loads which act downward on the top of the wall the vertical load may act eccentrically with respect to the wall thickness, causing weak-axis bending [1]. Also the wall is defined in the Part 1 of British Code 8110 in 1997, clause 1.3.4.1, as a vertical load-bearing element which its length exceeding 4 times its thickness, this definition identifies the walls from a columns [2].

RPC is one of the newest and most significant developments in concrete technology also known Ultra-High-Performance Concrete (UHPC). It is cementinous composites concrete with superior material properties like highly strength of compressive and tensile, high modulus of elasticity, extremely high ductility and durability, limited shrinkage, high resistance to corrosion and abrasion and fatigue resistance.. etc. The RPC mix which is characterized by dense mix, high cement content, crushed quartz or fine sand (with particle size less than 600 µm), silica fume, contains in most cases steel fibers to decrease its brittleness, new generation of superplasticizers, low w/c ratio (less than 0.2), and no coarse aggregate [3].

There have been some experimental studies reported on the walls in two-way action. Saheb and Desayi[4] tested 24 RC wall panels the walls were subjected to loads with eccentricity equal to one-sixth of panel thickness. They studied the influence of aspect ratio (H/L varied between 0.67 and 2.00), and other parameters on the ultimate strength of RC wall panels with cube compressive strengths of the concrete (f_{cu}) varied between (20 and 25) MPa. They concluded that the ultimate strengths for this case increase with the increase in aspect ratios (H/L).

Doh[5] was studied the effect of slenderness ratio (SR), aspect ratio (AR) and strength of concrete on the ultimate strength of concrete wall panels by testing six square concrete wall panels (3 of normal strength concrete and 3 of high strength concrete (HSC)) and four rectangular concrete wall panels, with constant eccentricity equal to one-sixth of the wall thickness and $\rho = 0.0031$.The strength for NSC = 40MPa and for HSC = 80MPa. Doh concluded from the experimental work that, the ratios of axial strength for normal and high strength concrete panels were found to decrease progressively with the increase in (H/t). The reduction in axial strength ratios in normal and high strength concrete panels was approximately (10.6 and 27.1 percent) respectively for an increase in H/t from (30 to 40).

The ultimate load of concrete wall panels does not increase linearly with the increase in strength of concrete. A 48.8% increase in strength of concrete causes only 3.3% increase in ultimate load. Ernest[6] experimentally tested ten small-scale RC wall panels simply supported along all the sides (two-way action) with f'_c =32 MPa, subjected to vertically uniformly distributed loading, (H/L) were between (0.5 to 1.0) and H/t were between (13 and 80), with thicknesses varied from (12 to 38) mm.

The steel reinforcement consisted of (25×25) mm spacing welded wire mesh single layer and it was placed centrally with respect to thickness, Ernest concluded that, at the center of the panel the highest stresses occur, at or near the ultimate loads. The possibility for the redistribution of stress, where vertical edge elements carry more load than center elements, was realized.

The test panels exhibited an abrupt type of failures. As an alternative, the tangent-modulus theory was also found to give reasonable estimates of failure loads by the use of tangent-modulus instability curves.

2. Experimental Program

The experimental program of this work includes studying the influence of two parameters on structural behavior of NSC and RPC wall panels subjected to axial eccentric compression loads in two–way action by testing six structural models reduced-scale wall panels, these models are divided into two groups, group one of NSC which contain 3 specimens and the second group of RPC which contain 3 specimens. The slenderness ratio (H/t) for all specimens is fixed at (18.75) with thickness for all panels of 40 mm. The parameters are;

1. Aspect ratio (AR): The values of aspect ratio (H/L) are (1.25, 1.50, 2.00).
2. The type of concrete (concrete strength (f'_c)): Two types of concrete mixes RPC and NSC are examined.

The values of the mechanical properties of hardened concrete, ultimate load capacity, Load-deflection relationship, and crack patterns are considered the indicators to denote the aims of this study.

3. Construction Materials

3.1. Cement

The Iraqi ordinary Portland cement (Mass) type (I) is used in this study.

3.2. Fine Aggregate

Two types of fine aggregate are used in this study;

A. Natural sand from Al-Ukhaidher region is used for NCS mixes of this study.
B. Extra fine sand, Anti-slip aggregate #4 with size (300-600) µm is used for RPC mix.

3.3 Coarse Aggregat

The maximum size of crushed gravel with (10 mm) from Al-Niba'ee region is used in NSC mix.

3.4 Silica Fume (Densified Microsilica MEYCO (MS 610))

MEYCO (MS 610) is a mineral additive that is used in RPC mix.

3.5 High Range Water Reducing Admixture (Superplasticizer S.P.)

A third generation copolymer-based superplasticizer, designed for the production of RPC mix is used (Glenium 51).

3.6 Ultra-fine Steel Fibers (Micro Steel Fiber)

Ultra-fine steel fibers are used throughout the experimental program. This type of ultra-fine straight steel fibers is manufactured by the Ganzhou Daye Metallic Fibers Co., Ltd, China. Micro steel fiber is the material of Reactive Powder Concrete (RPC). The diameter of the steel fiber is 0.2 mm and its length is 15 mm with aspect ratio (L_f /D_f) = 75.

3.7 Probuild SB (Epoxy Used)

In order to avoid any (1 mm or less) gab (if it is found) between tested specimen and the steel frame, an epoxy (Probuild SB) resin is filled inside this gab around the specimen for (7) days curing of epoxy to bracing (control) the fixity of the wall at supports.

3.8 Steel Bars

For reinforcement, welded wires fabric mesh is used and placed at the middle of specimen's thickness. These wires are (4mm) in diameter with fy = 720 MPa placed at (50mm) c/c spacing in both directions with 10mm concrete cover. In addition, a (10mm) steel reinforcement with fy= 556 MPa is placed around the wall to strengthen or protect the wall's edges as shown in Figure (1).

4. Wall Specimen Details

Panels are designed as (W x_1 x_2), where:
W: Refers to the word (Wall).
x_1: Refers to the type of concrete used (N= NSC & R= RPC).
x_2: Refers to the number of the wall panel within the group.
The details of the wall panels are summarized in Table (1).

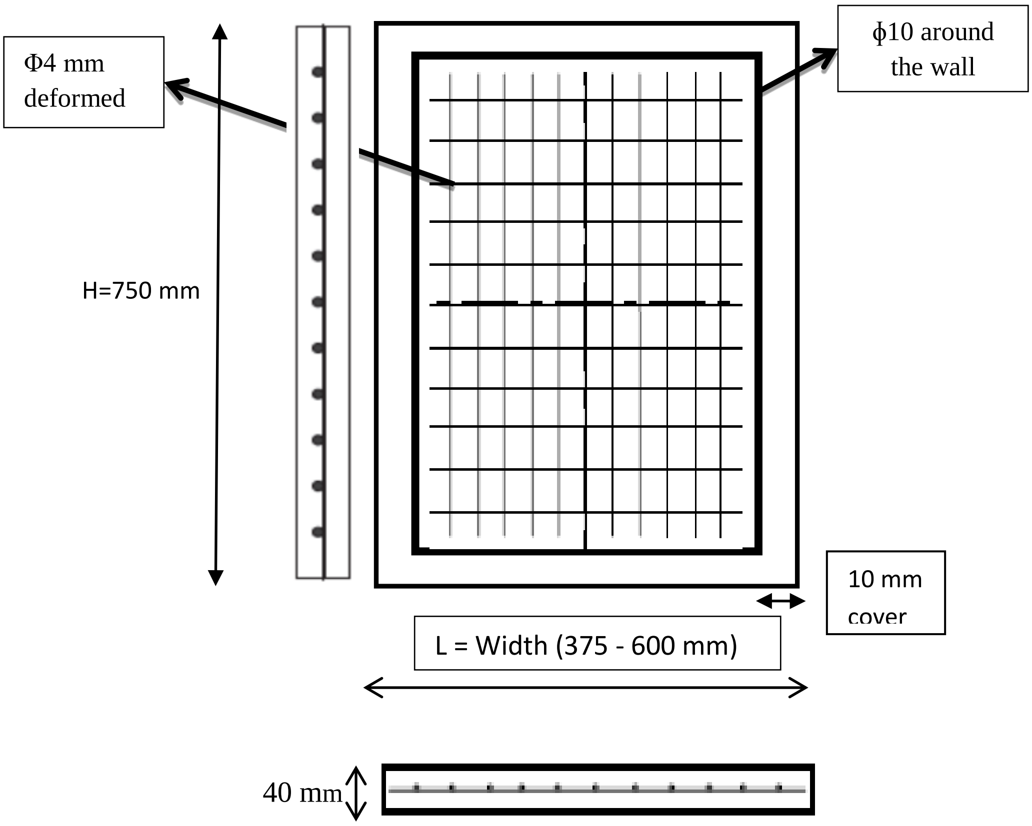


Figure (1): Arrangement of Reinforcement In Panel.

Table (1): The Details of The Wall Panels.

Wall panel	*Dimension (mm)*			*Aspect Ratio*	*Wall panel*	*Dimension (mm)*			*Aspect Ratio*
	H*	L**	T***			H	L	T	
WN1	750	600	40	1.25	WR1	750	600	40	1.25
WN2	750	500	40	1.50	WR2	750	500	40	1.5
WN3	750	375	40	2.00	WR3	750	375	40	2

*H: Height of the Wall.
**L: Wall Length.
***T: Wall Thickness.

5. Concrete Mix

5.1 Mix Proportion for NSC

The mix proportion for NSC is designed according to ACI Recommended practice ACI 211.1-91 [7].Groups 1 consist of NSC and material proportions which are 1: 1.29: 2.9 w/c=0.44 by weight, as shown in Table (2) below:

Table (2): Mix Proportions for Normal Concrete Strength.

Groups	*Cement (Kg/m^3)*	*Sand (Kg/m^3)*	*Gravel (Kg/m^3)*	*Water (Liter/m^3)*
1,2	415	535	1200	183

5.2 Reactive Powder Concrete Mix

Mix Proportions of RPC is shown below :

Table (3): Mix Proportions of RPC.

Cement (C)	880 kg	__
Fine Sand (S)	970 kg	__
Silica Fume (SF)	20%	Percent by weight of cementinous
	220 kg	__
Steel Fiber (V_f)	1.5%	Percent of mix volume
	118 kg	__
W/C	0.19	__
G51	7 %	Percent of cementitious materials (cement + silica fume) weight

6. Mechanical Properties Of Hardened Concrete

The average of the mechanical properties of concrete mixes used are listed in Table (4), the compressive strength test is carried out on three cylinders of (100 x 200mm) in accordance with ASTM-C39-86[8]. Flexural strength (modulus of rupture) test is carried out on three prisms of (100x100x400mm) in accordance with ASTM C 78-02[9]. While the indirect tensile strength (splitting tensile strength) test is carried out on three cylinders of (100 x 200mm) in accordance with ASTM C496-04[10].

Table (4): Mechanical Properties of Hardened Concrete.

Concrete Type	Compressive Strength (f'_c) MPa	Modulus of Rupture (f_r) MPa	Splitting Tensile Strength (f_{ct}) MPa
NSC	33.5	5.52	3
RPC	120.4	19.4	12.73

7. Wall Panels Testing Procedure

Before the testing day, the wall is lifted from curing container and the specimens are cleaned, wiped and painted in white color to ensure the crack pattern can be observed easily on wall surfaces and to attain clear visibility of cracks during testing.

After the test rig was fixed, the panel is fixed to the top and bottom supports and the wall panels are labeled and accurately placed along the edges of supports. Leveling the panel to ensure the perpendicularity of the panel the axial load is applied at eccentricity = t/6 from the center of specimens and the dial gages are placed at mid center of the wall panels. During the test, the applied loads and the corresponding mid-span deflections are recorded using dial gauge of 0.01mm accuracy and 25mm capacity located on the face of the wall panels. In the beginning of each test, about (2 kN) is applied to seat the supports and loading system, then the load is released after applying the seating loading, axial compressive loading is applied progressively in increments of (10 kN).This amount of gradual loading allowed sufficient number of loads and resultant deflections to be taken during the test which gives a realistic idea for the structural behavior of the wall panels. The ultimate axial load with its corresponding deflections at the center of the wall are observed and recorded, as shown in Plates (1) and (2) below.

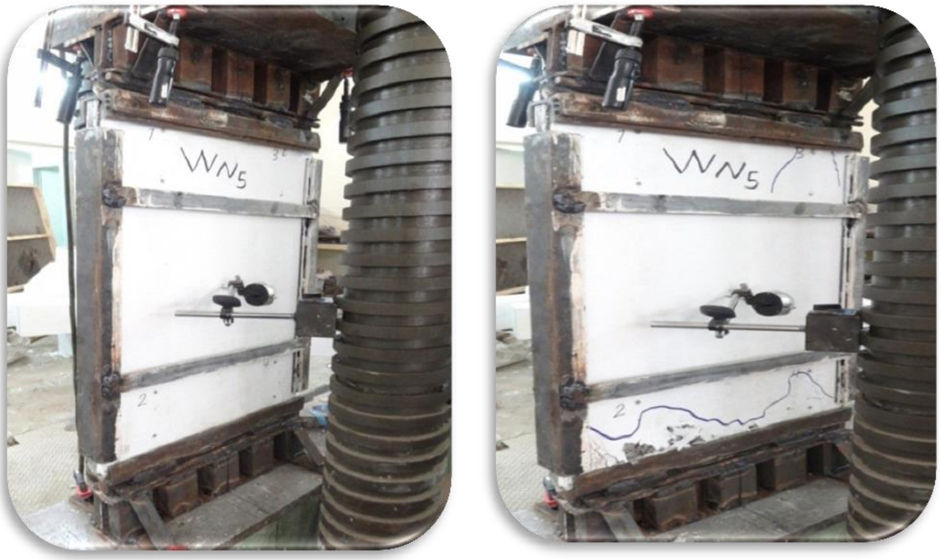


Plate (1): NSC Wall Panels Before and After the Test.

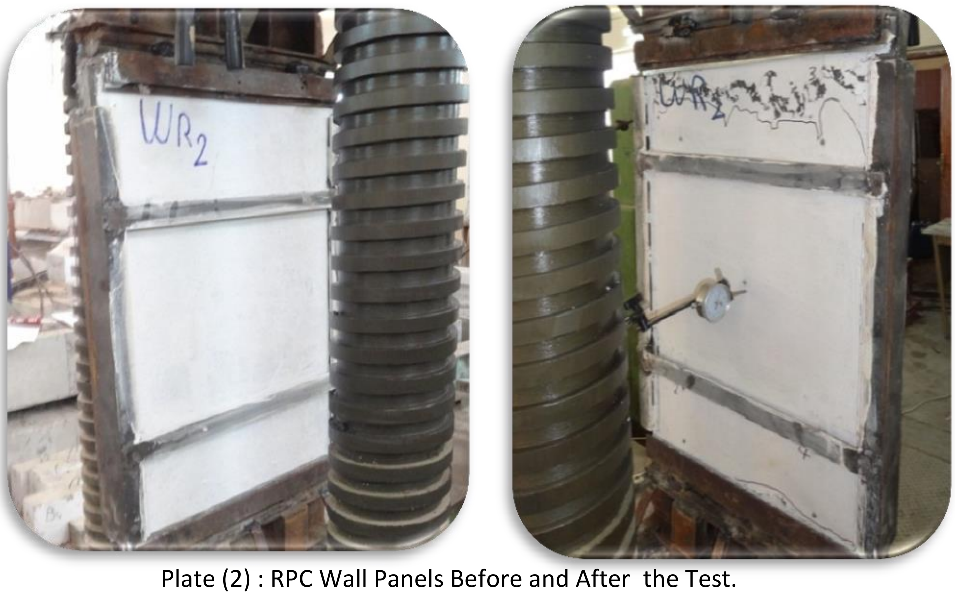


Plate (2) : RPC Wall Panels Before and After the Test.

8. Test Results

8.1 Axial Failure Loads and Lateral Deflection for Concrete Wall Panels

The failure loads and lateral deflection for all the panels tested in this study are presented in this section to investigate the effects of two parameters ; aspect ratios (H/L) and concrete type (concrete strength (f'_c)) on ultimate axial load capacity and lateral deflection of thin concrete wall panels.

Table 5 presented the results of axial load of specimens and their corresponding lateral deflection.

Table 5: Results of Axial Load of Specimens and Their Corresponding Lateral Deflection.

Wall Panel	Experimental Results (kN)	Lateral Deflection (mm)	Wall Panel	Experimental Results (kN)	Lateral Deflection (mm)
WN1	480	1.38	WR1	1500	1.98
WN2	410	2.92	WR2	1260	1.315
WN3	300	3.17	WR3	920	1.19

8.1.1 Effect Of Aspect Ratio (AR) On Ultimate Strength And Lateral Deflection

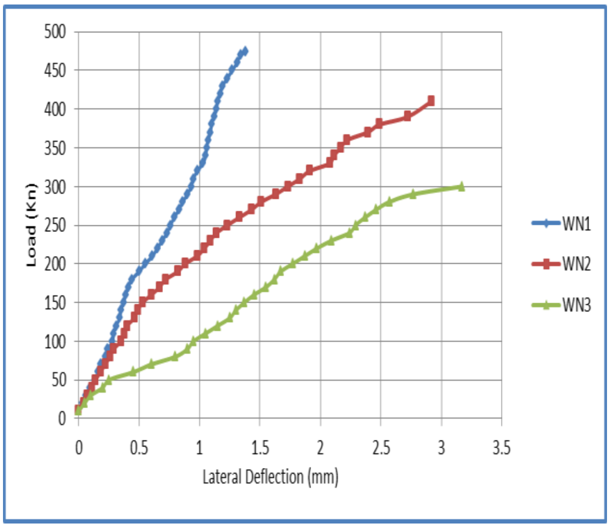


Figure (2): Effect of AR on Load-deflection Behavior for NSC.

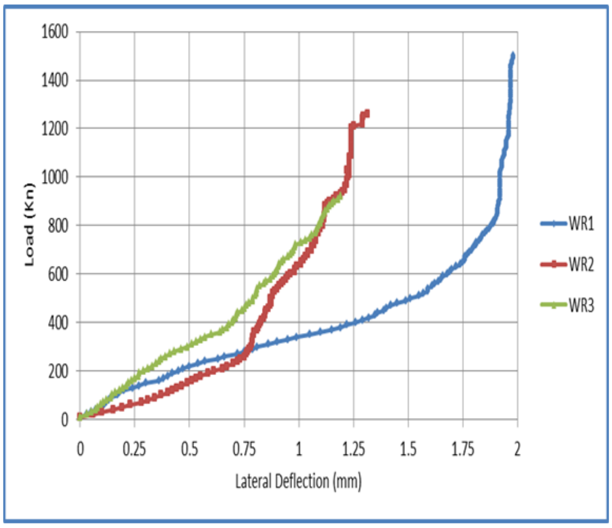


Figure (3): Effect of AR on Load-Deflection Behavior for RPC.

From Table 5 and Figures (2) and (3) it can be seen:

- The ultimate strength of the RC wall panel decreases with the increase in AR from (1.25 to 2.00).
- The decrease in ultimate load for NSC wall panels is about 14.6 % and 37.5%, for an increase in AR from 1.25 to 2.00.
- The decrease in ultimate load for RPC wall panels is about 16% and 38.7% , for an increase in AR from 1.25 to 2.0.

- The increase in aspect ratio results in the increases in lateral deflection for **NSC** wall panels. The increase in lateral deflection is about (2.3 times) when reduced AR from 2.00 to 1.25 and about (1.09 times) when reduced AR from 2.00 to 1.50, also the increase in lateral deflection about (2.12 times) when reduced AR from 1.50 to 1.25.
- For RPC wall panels, the increase in aspect ratio results in the decrease in lateral deflection. The reduction in lateral deflection is about (1.66 times) for an increase of AR from 1.25 to 2.00, and about (1.51times) for an increase of AR from 1.25 to 1.50, also the reduction in lateral deflection is about (1.11 times) when AR is increased from 1.5 to 2.0.
- This reduction in ultimate strength is due to decreasing in the width (loaded area (L)) of wall panel.

8.1.2 Effect of Type of Concrete (concrete strength (f '$_c$)) on Ultimate Strength and Lateral Deflection

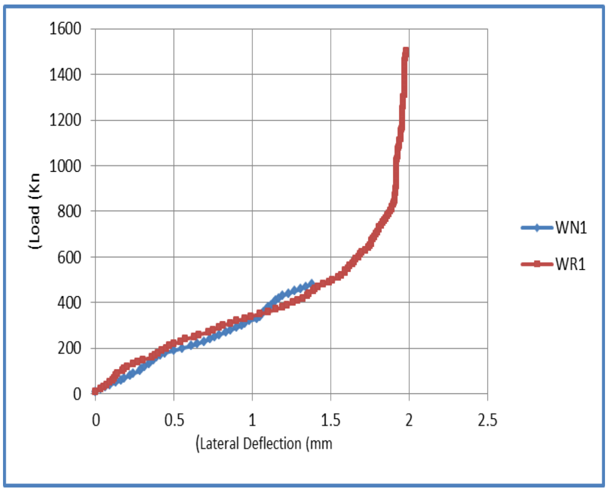


Fig (4): Effect of($f\,'_c$) on Load-deflection With (AR= 1.25).

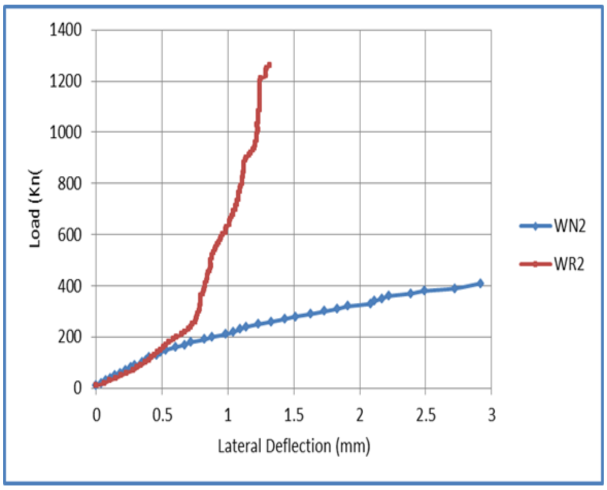


Fig (5): Effect of ($f\,'_c$) on Load-deflection Behavior Behavior With (AR= 1.50).

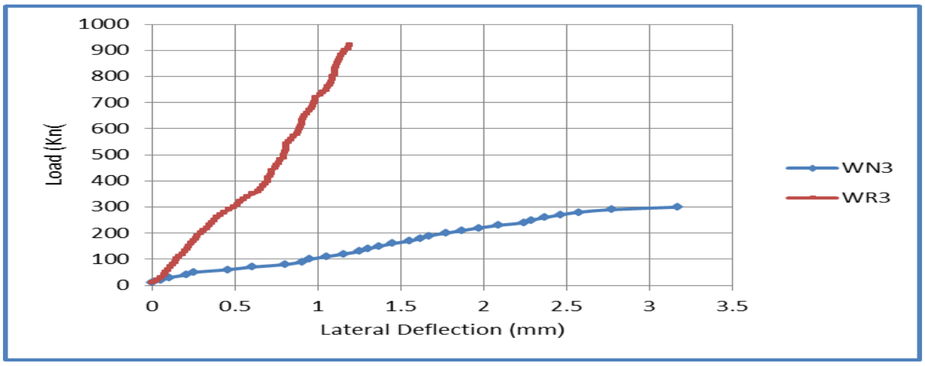


Fig (6): Effect of ($f\,'_c$) on Load-deflection Behavior With (AR=2.00).

From Table 5 and Figures (4, 5 and 6), it can be seen:

- It is evident that the concrete compressive strength has an obvious influence on the axial strength for concrete panels.
- The increase in axial strength, when increased the concrete strength (f'_c) from 33.5 (MPa) to 120.4 (MPa) is about (212.5, 207.3, 206.67) % for panels with H/L = (1.25, 1.50, 2.00), respectively.
- RPC wall panels exhibit less lateral deflection than NSC.
- When increased f'_c and change concrete type from **NSC** (f'_c =33.50 MPa) to RPC (f'_c =120.4 MPa), the lateral deflection reduced as follow ;
- When AR= 1.50 the reduction is about (2.22 times).
- When AR= 2.00 the reduction is about (2.66 times).

As concrete strength of the wall panel increases from (33.5 to 120.4) MPa, the lateral deflection decreases, because the development of strength of compressive for Reactive Powder Concrete may come from the effect of superplasticizer (G51) as a water reduction on compressive strength, and because of the low water ratio used in preparation of RPC mixes. In addition to the chemical reaction of (pozzolanic materials), micro silica fume with calcium hydroxide, released from hydrated cement leads to improve the compressive strength and structural behavior, also reduce the micro cracking, reduce voids and strengthen the microstructure.

From Figures (2 to 6) can be shown that RPC wall panels have less deflection during the loading phases than the NSC wall panels, reinforced with same reinforcement ratio, however, the ultimate deflection (at failure) in RPC was still lesser than the NSC due to the usage of steel fibers. The ultimate deflection was varied depending on concrete type (concrete strength (f'_c)) and aspect ratio H/L. This improves the compliance of the RPC wall with the serviceability limits. In general, all RPC wall panels exhibited significant increase in stiffness and ultimate capacities, by comparison with the NSC wall panels.

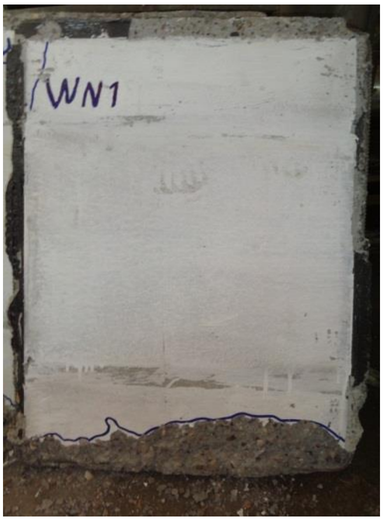
8.2 Cracking Patterns and Failure Mode.

8.2.1 Crack Pattern for NSC Wall Panels and Failure Mode

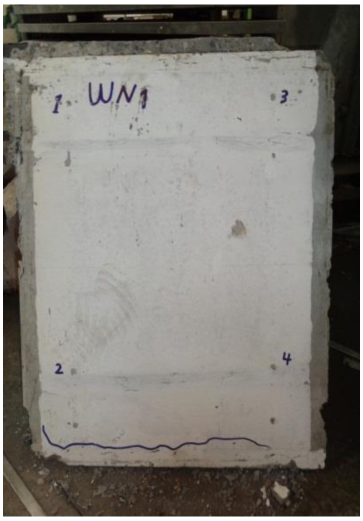
Plates from 3, 4 and 5 show the crack patterns observed on the compression faces and the tension faces of the tested NSC wall panels after failure.
The crack patterns of panels WN1on the compression face, exhibit non-straight cracks near bottom edges of the panel in the region of 1/3 height of the wall. These cracks are horizontal and perpendicular to the direction of loading with some tiny diagonal cracks which appear near the corners of the WN1 wall panels. In tension faces, one horizontal main crack appears in the bottom edges of wall panels.

The reason for diagonal cracks is that, some twisting moments occur near the corners. This may be caused by the inequality of the edge of the wall, which generates inequality in loading. The holding down of the side edges by the side supports and the application of eccentric loads onto the loading edges, all this may cause torsional cracks. The crushing failure mode is expected considering the low slenderness ratio ($H/t_w < 25$) of the wall tested.

The crack patterns of panels WN2, WN3 on the compression face, exhibited non-straight cracks near top edges of the panel in the region of 1/3 height of the wall. These cracks are horizontal and perpendicular to the direction of loading. In the tension faces of panels WN2, WN3 one horizontal crack along the width of wall appears in the top edges of wall panels with small minor cracks branched from the horizontal crack downwards on the tension face of panel WN2 and WN3 and one vertical crack along the edge of WN2 also one diagonal crack in the corners of tension face of panel WN2. The reason for diagonal cracking is mentioned in the previous paragraph.



Plate(3) A: Compression Face.



Plate(3) B: Tension Face.

Plate (4) A: Compression face.

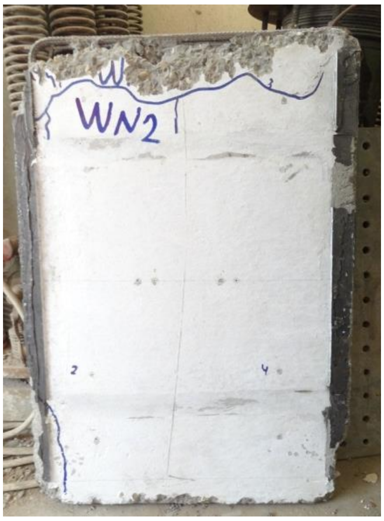
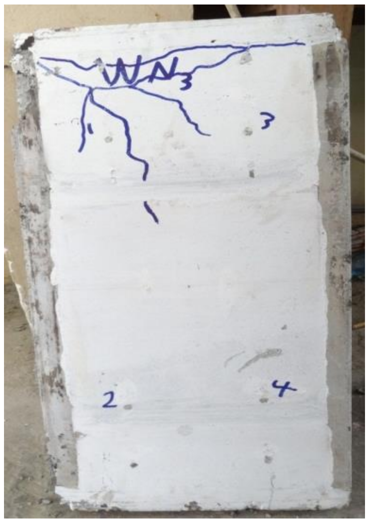


Plate (4) B: Tension face.

Plate (5) A: Compression Face.



Plate(5) B: Tension Face.

8.2.2 Crack Pattern for RPC Wall Panels and Failure Mode

Similar to the NSC wall panels, the crack patterns of panels WR1 (Plate 6 A&B) on the compression face, exhibit non-straight cracks near bottom edges of the panel (crushing) in the region of 1/3 height of the wall. These cracks are horizontal and perpendicular to the loading direction with some fine vertical and inclined cracks on the compression face of the WR1 wall panels. In tension faces one non-straight horizontal main crack appears in the bottom edges of wall panels WR1.

The crack patterns of WR2 (Plate 7 A & B) on the compression face, exhibit non-straight cracks near top edges of the panels WR2 (crushing) in the region of 1/3 height of the wall. These cracks are horizontal and perpendicular to the loading direction, for compression face of WR2 shows a series of horizontal crack along the width of panel (crushing) and some cracks branched from near the top region of the wall WR2 and spread vertically downwards also inclined cracks near the edges of wall WR2, for compression face of WR3 (Plate 8 A&B). One horizontal crack has been formed when the load reaches near the ultimate load in the bottom edge of panel also one diagonal crack in the corners of panel, the reason for diagonal cracking is mentioned in the 8.2.1 section.

In the tension faces of panels WR2, WR3 horizontal cracks along the width of wall appear in the top edges of wall panels and one fine horizontal crack appears on the bottom edge of WR2. A comparison of crack pattern can be made here between the identical NSC and RPC walls supported on all sides, RPC wall panels show a more ductile failure mode than NSC, with possibly of some yielding of reinforcement taking place. In addition, a torsional mode of failure near the corners of some of walls is observed. The torsional failure mode may have contributed to an additional reduction in load capacity.

Plate (6) A: Compression Face.

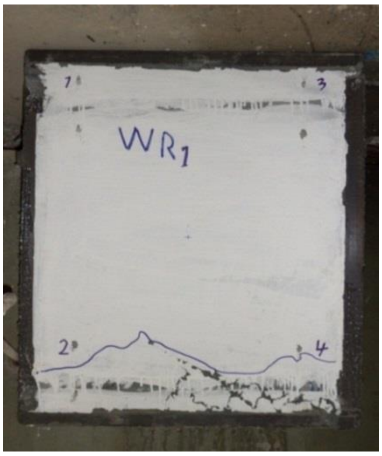


Plate (6) B: Tension Face.

Plate (7) A: Compression Face.

Plate (7) B: Tension Face.

Plate (8) A: Compression Face.

Plate (8) B: Tension Face.

9. Conclusion

From the test results of the experimental program the following conclusions are obtained:

1. In general the ultimate strength of the wall panel decreases with the increase in AR.
2. The ultimate strength of the concrete wall panels under two-way compression eccentric loading increases with the increase in concrete strength (f'_c).
3. The increase in aspect ratio (H/L) from 1.25 to 2.00 of NSC panels causes an increase in the lateral deflection of the concrete wall panels, while for RPC wall panels; the increase in aspect ratio (H/L) from 1.25 to 2.00 causes a decrease in the lateral deflection of the concrete wall panels.
4. As concrete strength of the wall panel increases from (33.5 to 120.4) MPa, the lateral deflection decreases.
5. Specimens with RPC show larger deformation capacity than NSC under the same axial load.

Abbreviations

RPC	Reactive Powder Concrete.
NSC	Normal Strength Concrete
ACI	American Concrete Institute
BS	British Standard
RC	Reinforced Concrete
AR	Aspect Ratio

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