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Enhancement of A Sustainable Performance of Prismatic and Non-Prismatic Plane Concrete Frame Under Static Load

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Abstract

This research investigates experimentally the reduction of gases emitted from a plane concrete frame by reducing the amount of concrete due to the use of non-prismatic cross-sections. The study includes casting three frames using normal-strength concrete. Two plane frames with non-prismatic cross-sections of the columns and beam and one frame with prismatic cross-sections. The amount of concrete used for all three specimens is the same. The frame was tested under static load by two concentrated loads on the beam. The results showed that the use of non-prismatic sections improves the performance of the concrete frame and increases the load capacity of the frame in the same amount of concrete, so the cost of the project and the gases emitted can be reduced through the use of non-prismatic sections. The ultimate load of the non-prismatic concrete frame with columns and beam increases by 25% and 16%, respectively. Using non-prismatic sections decreases the frame's stiffness (at beam and columns) and using non-prismatic sections in the beam, the frame's shear failure is improved and less fragile than the prismatic sectional frame.

Keyword: prismatic, non-prismatic, frame, concrete and static load.

1. Introduction

Achieving the basic requirements of the buildings using the minimum amount of materials are considered an optimal design of the structure [1–3]. Reducing the economic cost of concrete buildings has attracted many researchers to reach the optimal design of concrete frames [4–8]. Reinforced concrete non-prismatic beams are often used because they offer some structural and nonstructural advantages over prismatic elements, such as stiffness or moment capacity to self-weight ratio, providing a smaller effective height at mid-span for supporting frames (bridges and buildings) which eases the placement of different facilities (i.e., air conditioning, piping) along the building. Nevertheless, in some countries, reinforced concrete non-prismatic beams or columns are unlikely a common structural solution in buildings because their use involves higher construction costs, as special formwork and qualified construction workers are required. Reinforced concrete non-prismatic beams in midrise framed buildings in Latin American countries like Mexico and Ecuador or in European countries like Germany (Fig. 1) [9] .

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Fig. 1. Urban bridge with RC non-prismatic beams in downtown Seattle [9]

Many researchers dealt with the study of non-prismatic sections in all concrete members because of this topic of practical importance to meet the structural requirements of buildings and bridges, where Kadhim [10] presented a theoretical study of a concrete frame with prismatic and non-prismatic members under cycle loads in which he studied the change of the cross-sections of the beam. Tena-Colunga [11] presented an experimental study of prismatic and non-prismatic simply supported concrete beams with different angles of non-prismatic beam under shear loads.

Dawood [12] studied a continuous non-prismatic beam (tapered) under static loads, while Ghadhban [13] studied a simply supported non-prismatic beam hollow section retrofit with carbon fiber reinforced polymer (CFRP) under two-point loads. Al-Ali 2022 [14] presented experimental research to study prismatic and non-prismatic (tapered) reinforced concrete beams under static load. It was discovered that increasing the angle of inclination of the beam (decrease in depth) reduces the ultimate load, as it decreases by 4%, 14%, and 21% for angle inclination 7°, 14°, and 21°, respectively.

This research included a practical study of a plane prismatic and non-prismatic reinforced concrete frame for the beam and columns for the purpose of distributing concrete optimally to obtain better ultimate load resistance and reduce the amount of redundant concrete as well as reduce the gases emitted from concrete and reinforcing steel. This work included casting three specimens using normal-strength concrete and testing them under two constructed loads. The amount of concrete for all three specimens is equal. The external dimensions of all specimens are equal, where the length of the columns is 1000 mm (from the base of the column to its top) while the length of the beam is 1000 mm (from the outer edge of the beam to the other edge). The cross sections of non-prismatic columns (F-NC) change between (170*150) mm at the top of the column to (130*150) mm at its base, while the cross sections of non-prismatic beams (F-NB) change between (170*150) mm at the edges of the beam to (130*150) mm in the middle. The ratio of the largest dimension to the smallest dimension in non-prismatic members was determined to be 1.3[10]. The third frame was prismatic with the beam and columns (F-P), as it has a cross-section (150 * 150) mm with the

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beam and columns. Comparisons include the ultimate load of specimens, first crack load, load-deflection curve at the mid-span of beam, crack pattern, and deflected shape for frames.

2. Methods and Materials

All the materials used to complete the experimental work of this research were dealt with in this section in addition to the formation of the supports used and the device and methods of applying the loads as well.

2.1. Type of Concrete

Normal strength concrete was used in this research, which consisted of cement, fine aggregate, and coarse aggregate. All the materials used are compline to the standard specification of ASTM .The concrete mix proportions for one cubic meter were determined based on several trial mixes that were designed according to (ACI 211.1-2004) [15]. (Table 1) shows the weight and proportion ratio of the trial mix used for this study.

Table 1. The proportions of materials for the trial mix used

Materials	Cement	Fine aggregate	Coarse aggregate	Water
Weight (kg)	380	736	1024	205
Ratio	1	1.94	2.69	0.53

The mechanical properties of the concrete can be summarized in Table 2. The compressive strength was tested according to BS,1981 part 116 [16] by taking an average of the results of three cubes (150*150*150) mm. The flexural test were tested according to ASTM C78- C78m-15a [17]. The modulus of elasticity of normal strength concrete was calculated according to the (Eq.1) [18].

Table 2. Mechanical properties of the concrete*

The properties	f_{cu} (Compressive strength) (MPa)	f_r (flexural strength) (MPa)	*Ec (Elasticity modulus) (MPa)*
Concrete	30.18	3.38	23,094

* The tests were carried out in the laboratories of engineering consulting bureau of the university of Kufa- faculty of Engineering.

f_{cu}: compressive strength, tested by using average of three cubes 150*150*150 mm.
f_r: flexural strength, tested by using average of three prisms with 100*100*400 mm Using Simple Beam with Third-Point Loading.
Ec: modules of elasticity of conventional concrete by $E = 4700\sqrt{f_c'}$ (MPa) (1)

2.2. Details of Reinforcing Specimens

In this study, a deformed steel reinforcement bar was used. A reinforced bar with a diameter (Ø10mm) was used for the longitudinal reinforcement of the beams and columns, while a reinforced bar with a diameter (Ø6mm) was used for the stirrups and ties for all specimens. The properties and details of the reinforcing steel for the tested specimens are shown in **(**Table 3**)** and **(**Fig. 2**)**, where the reinforcing steel for the beam and columns was designed according to (ACI 315-19) [17].

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Table 3. Results of steel reinforcement bar tests

Nominal diameters (mm)	Yield stress (MPa)	Ultimate stress (MPa)	Modulus of elasticity (MPa) [a]
10	471	664	200000
6	422	605	200000

[a] The modulus of elasticity of steel reinforcement is assumed.
* The tests were carried out in the laboratories of engineering consulting bureau of the university of Kufa- faculty of Engineering.

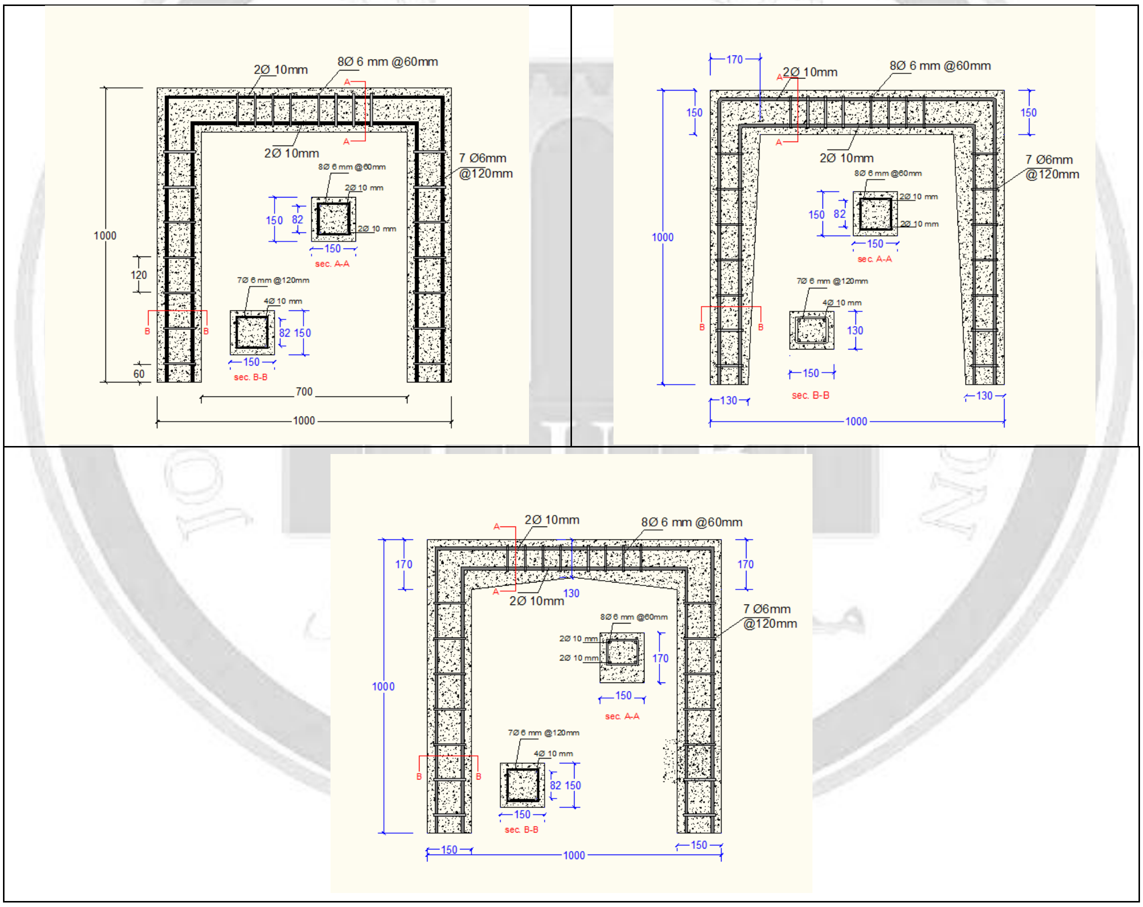

Fig. 2. Details of steel reinforcement for tested specimens

2.3. Supporting and Loading Condition

Two points loads were subjected on the beam, and the distance between them is 300 mm. The rubber plates were placed under the load concentration to avoid the occurrence of stress concentration in that area, thus preventing the occurrence of local crashing, while to avoid the event of local crashing of the supports, cups support was placed under each column. “The supporting of the cups was approximately fixed. The proof for that is the rotation in the deflected shape of the columns near the cups is approximately zero or minimal values at the large loads” [19]. so, the benefit of the cup support, in addition to preventing the local crushing of the concrete, is to obtain a fixed support, which is the closest in practical structures. Fig. 3 shows the dimensions of the cup supports and specimen ready to test.

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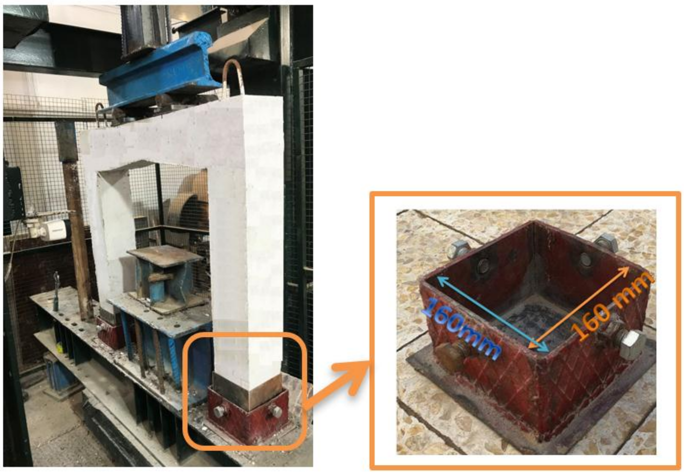

Fig. 3. Final setup of testing specimens and dimension of cup supports

3. Experimental Results

This section deals with an experimental study of the research and is divided into four parts (first crack and crack width, ultimate load and type of failure, load-deflection curve at mid-span beam, and Deflected shapes for frames). The tests were carried out in the university of Kufa- faculty of Engineering.

3.1. First Crack and Crack Width

The behavior of the visible cracks in all the specimens tested was almost similar. Cracks began to appear in the lower part in approximately the middle of the beam, and then with continuous loads being applied, cracks began to appear and propagate in all parts of the beam. The outer face of the columns, especially the upper part of it, also suffers from cracks in the specimens F-P and F-NB. While specimen F-NC, cracks do not appear in columns due to the large size of the cross-section of the upper part, as shown in the Fig. 4.

The first visible cracking load of the control frame (F-P) was 45kN. In the F-NC frame, the first crack load increases by 7% due to the small clear span of the beam, which was 6% smaller than the beam span of the control frame due to the non-prismatic columns section. While for the F-NB frame, the first cracking load was reduced by 33% due to the small depth of the beam, especially in the middle, which was 13% smaller than the beam depth of the control frame.

The width of the cracks for all the tested specimens for each load applying gradation was measured. A crack meter with an accuracy of 0.01 mm was used to measure the crack width for all specimens. Table (4) shows the first visible crack load and crack width.

Fig. 4. Crack pattern for the tested frames

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Table 4. First crack load and crack's width

No.	model's name	prismatic and non-prismatic	first crack load (kN)	load (kN)	crack's width (mm)
1	F-P	prismatic beam and columns	45	50	0.05
				100	0.18
				160	0.25
2	F-NC	prismatic beam and non-prismatic columns	48	70	0.2
				100	0.25
				160	0.4
3	F-NB	non-prismatic beam and prismatic columns	30	60	0.15
				100	0.43
				160	0.57

3.2. Ultimate Load and Type of Failure

The use of non-prismatic sections (Tapper) with equal proportions in the columns and the beam increases the ultimate load of the frame in different percentages. Fig. 5 shows the percentage increase relative to the control frame. However, the type of failure in all specimens did not change despite the change in the geometric shapes of the members, where shear failure was controlled for all specimens.

The ultimate load of the F-NC was increased by 25% more than the control frame due to decrease in the length of the shear span by 10% as a result of the large upper part of the column as a result of using a non-prismatic section in the columns. For the smallest value of the shear span, the applied load is directly transferred to supports by the compression struts due to arch action, which increases shear strength. On the other hand, when the shear span increases, the effectiveness of the compression strut in transferring the load is decreased resulting in a decrease in the ultimate strength of the specimens. [20]

The failure behavior of the F-P and F-NC specimens was fragile, as a sudden failure of shear occurs. While the behavior of the F-NB specimen was less fragile, as many cracks appear and a large deformation occurs compared to other specimens before failure, because the presence of non-prismatic sections develops arch-action theory and makes the distribution of damage along the taper before the formation of diagonal shear cracks, and this confirms the results of previous research on the non-prismatic beams [21] and [22].

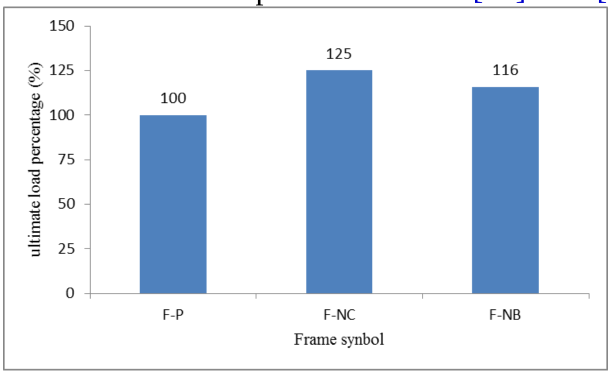

Fig. 5 Percentage of the ultimate load of the tested frames

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3.3. Load-deflection Curve at Mid-span Beam

Fig. 6 shows the relationship between the applied load and the deflection at the mid-span of the beam for the tested frames. The deflection behavior was similar for all specimens, where the load-deflection curve was linear until the first crack, and then it behaved non-linearly. The inclination of the F-NC load-deflection curve is lower than that of the control frame (F-P), due to the small length of the beam that more affects the deflection. While the G-NB frame was less stiff than the control frame due to the small depth of the beam that effect on the moment of inertia of the beam.

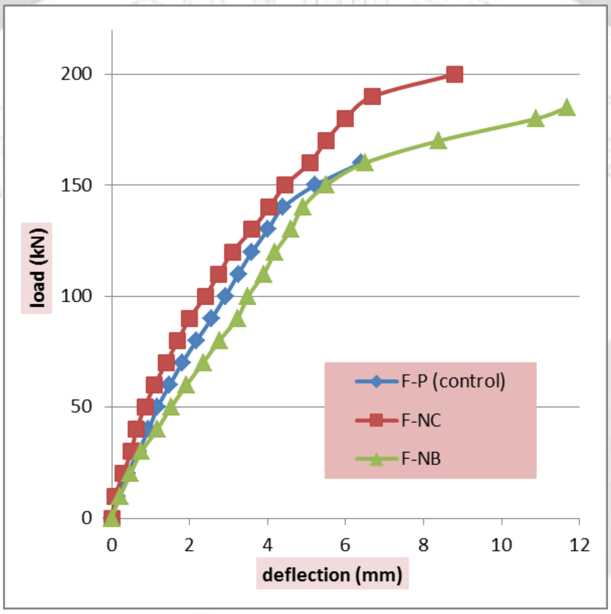

Fig. 6. load-deflection curves at mid-span of beams for tested frames

3.4. Deflected Shapes for Frames

The deformation of the whole frame relative to the load increase for all the specimens tested was shown in Fig. 7. The use of non-prismatic sections increases deformations before failure. In the F-NC specimen, the deflection of the beam was more than the control frame, especially in the loads close to the collapse loads, while the F-NB specimen notices a high deformation in the beam as well as the columns. Therefore, this feature is taken advantage of by the specimens that fail in shear (as in the specimens of this study) by making the specimen less fragile.

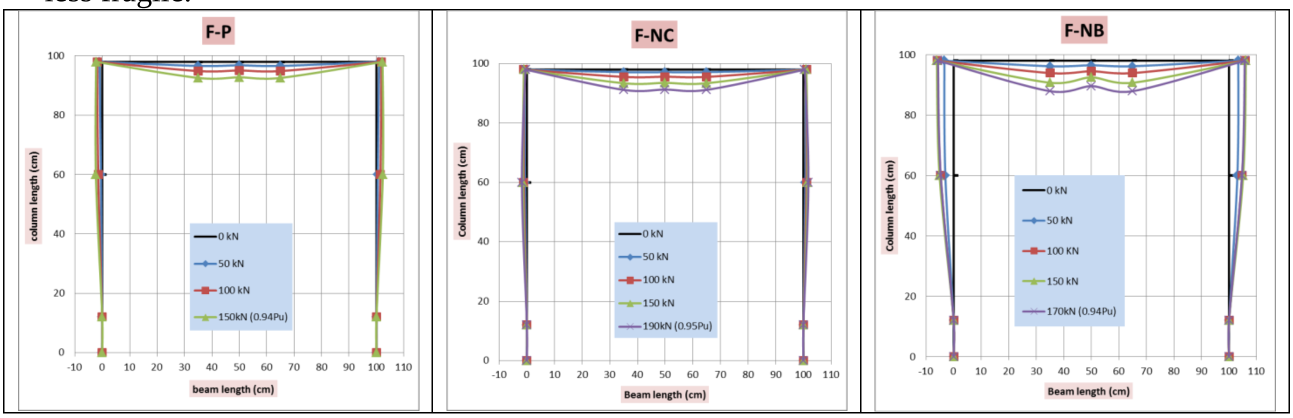

Fig. 7 deflected shape of frames tested (All deformation values are multiplied by 10)

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3.4. Stiffness of Frames

Stiffness is the force required to produce one unit of deformation in a member. The initial stiffness can be calculated by determining the slope of the load-deflection curve at the servicing stage (the ratio of the load at 65% of the ultimate load of the specimen to the corresponding deflection) [23]

The initial stiffness results are presented in Table (5). Where results show a decrease in the initial stiffness of the specimens F-NC and F-NB by 20% and 16% compared to F-P, respectively. These results confirm the results of previous research Tena-Colunga at 2008 [11] and Balduzzi at 2016 [24], in that the presence of a non-prismatic section reduces the stiffness of the member as a result of the formation of cracks in the shear direction before shear failure.

Table (4-10) Stiffness results of the specimens tested under static load

Name Sp.	0.65 P_u (kN)	Deflection at 0.65P_u (mm)	Stiffness (K_i) (kN/mm)	$\frac{K_i^* - K_c^{**}}{K_c}$ (%)
F-P	104	3.05	34.1	-------
F-NC	130	4.75	27.4	-20
F-NB	120	4.2	28.6	-16

* Initial stiffness of specimens.
** initial stiffness of control specimen.

4. Conclusions

This paper presents the results and interpretations of three specimens of prismatic and non-prismatic reinforced concrete plane frames. The variables of this study included the use of variable cross-sections in beam and columns to study their effect on the behavior of the frame, reduce the cost of construction, and their suitability for a friendly environment. The most important conclusions reached can be summarized in the following points:

1. The ultimate loads of the concrete frame increase by 25% and 16% for the non-prismatic frame in columns and beam respectively for the same amount of concrete used.
2. The stiffness of the concrete frame increases when a non-prismatic concrete frame was used in the columns.
3. The results confirmed that the use of a non-prismatic concrete frame in the beam makes the shear failure less brittle.
4. The use of a non-prismatic frame reduces the amount of concrete and reinforcing steel necessary to resist intended loads, as well as reduces the gases emitted and the total cost of the project.

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تحسين الأداء المستدام للإطار الخرساني المنشوري وغير المنشوري تحت الحمل الساكن

ضرغام حسين علي   مصطفى بلاسم داوود   غالب محسن حبيب

قسم الهندسة المدنية/ كلية الهندسة/ جامعة بابل/ العراق

الخلاصة

هذا البحث يتحرى عمليا تقليل الغازات المنبعثة من الهيكل الخرساني المستوي عن طريق تقليل كمية الخرسانة نتيجة استخدام مقاطع غير منشوريه (المدببة) تحت حمل ساكن. الدراسة تتضمن صب ثلاث هياكل خراسانية ذو مقاومة اعتيادية. هيكلان مستويان بمقاطع عرضية غير منشوريه بالأعمدة والعتبة وهيكل خرساني بمقاطع منشوريه. جميع الهياكل فحصت تحت حمل ساكن عن طريق تسليط حملين مركزين على العتبة. النتائج بينت تحسن في اداء الهيكل الخرساني عند استخدام مقاطع غير منشوريه وزيادة في سعة تحمل الهيكل وبنفس كمية الخرسانة المستخدمة، لذلك كلفة المشروع والغازات المنبعثة يمكن تقليلها باستخدام مقاطع غير منشوريه. الحمل الاقصى للهيكل الخرساني ذو مقاطع غير منشوريه بالأعمدة والعتبة تزداد بمقدار ٢٥% و١٦% على التوالي. استخدام مقاطع غير منشورية (الاعمدة والعتبة) يقلل صلادة الهيكل الخرساني ويحسن خصائص فشل القص ويجعله اقل هشاشة.

الكلمات الدالة: الحمل المنشوري وغير المنشوري ،الإطار والخرسانة ،الحمل الساكن.