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Onsite Load Bearing Capacity of Curved-up versus Straigt Beams

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Abstract

Straight and curved-up beams are cast as part of the frame models. The models are made as single-span, double-span, and triple-span models. Experimental investigation is conducted to predict load capacity of curved-up beams compared to straight beams. Six models: single-span, double-span and triple-span are presented. Onsite, masonry blocks and bricks, steel pipes and gravel are used to load the beams uniformly. Load is applied gradually until failure mechanism. Enhancement to load capacity is observed in the range between 8.67% to 14.12%. The average enhancement ratio can be taken as 11% due to curved-up effect. Load capacity of interior curved-up beam/span will enhance by 120.3% and 131.3% for both straight and curved-up beams.

Keywords: Curved-up, Straight, Beams, Camber, Load capacity

Introduction

Most commonly used systems in practice are portal frames and trusses. However, truss system is not common if reinforced concrete is to be used, due to the difficulty of formwork and, thus, portal frames are usually used.

The importance of the effect of axial force on behavior of the member is proved, especially for long/slender members. Axial force can be actioned/motivated in curved-up (cambered) members.

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This point gives rise to the concept of using geometric nonlinearity because it builds the procedure of structural analysis on large deformations, also on geometry of the member after occurrence of these large deformations. As a result, this non-linear behavior controls the sequence of plastic hinge formation and their expected locations.

Generally, geometric nonlinearity occurs whenever the magnitude of displacements affects the response of the structure. This may be caused by large deflections or rotations.

Literature Review

Troxell et al. (1968) found that failure load (load capacity) under sustained load for a long time is less than that for short time tests. Price (1951) showed that failure load ratio may be within the range (80-82%). Nilson et al. (1986) stated that in concrete, lateral expansion is restricted by adjacent strips resulting in a slight strengthening and stiffening.

Westergaard et al. (1921) considered membrane action in reinforced concrete and noticed a significant increase in load carrying capacity due to arching. Brotchie et al. (1971), Cotsovos et al. (1990), Roberts (1968) have reported similar results.

Vessali (2015) found that compressive strength of concrete has negligible influence on peak load of tensile membrane action.

Tharmarajah et al. (2023) reported that failure load was 80–100% higher than the flexural strengths predicted by Eurocode and ACI 440.1R. The increased failure load of restrained slabs and strength of unreinforced slab can be attributed to compressive membrane action, which is not considered in many design codes to determine strength of in-plane restrained reinforced concrete slabs.

Wang et al. (2021) stated that the contribution of membrane force to resistance of slabs is negative under compressive action. It is gradually shifted to positive after mobilization of tensile action when the tension zone in the center of the slab develops into a certain area. Tensile forces in the tension zone can offset compression force near the edge.

Regan (1975) stated that catenary or tensile membrane actions may prevent local damage to a structure spreading to cause a progressive collapse. In the sense of sustainability, Smarzewski (2018) conducted experimental and analytical investigation of behaviour and load-carrying capacity of deep beams with openings (DBO) and without openings (DB) made of hybrid steel-polypropylene fibre-reinforced high-performance concrete (HFRHPC) subjected to three-point bending tests with a gradually increasing load until failure. The conducted study demonstrates that hybrid fibres as web reinforcement have a favourable impact on deep beam crack widths and raise the load carrying capacity of deep beams with openings.

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Sustainably, Kumar et al. (2022) discussed properties of dried sewage sludge (SS) and its influence on microstructure development of HVFA (High Volume Fly Ash) concrete when used as a partial replacement of the binder material. Their study reveals that the compressive strength of concrete specimens decreases with the increase in replacement level of SS. The addition of SS as a binder to concrete has a lower environmental impact embodied energy, CO2 emission, and cost per unit strength.

Liu et al. (2012) and Mirghaderi et al. (2021) presented the theoretical effect of column-to-beam strength ratio and axial compression ratio on failure mechanism of concrete-filled square steel tube frame structures.
The author encourages further investigation to effect of curved up on strength behavior of sustainable construction materials.

Methodology
Models: Six models are presented in this study, details of which are shown in **Table 1** and **Fig. (1)**.

Table 1 Details of study models

Model	No. of Spans	Beam Type	f'_c (N/mm^2)	Beam Reinforcement
F1	Single	Straight	26.6	1 – φ 5 mm Top & Bottom
F4		Curved-up		
F2	Double	Straight	26.6	1 – φ 5 mm Top & Bottom
F5		Curved-up		
F3	Triple	Straight	26.6	1 – φ 5 mm Top & Bottom
F6		Curved-up		

Geometric Details:
Details of six portal frame models are shown in **Fig. (2)**.

Load Application:
Due to non availability of mechanical equipment/machines to apply experimental load, masonry concrete blocks, masonry bricks, steel circular hollow sections (pipes) and sacks filled of gravel are used to load beams in a similar fasion of uniform load as shown in **Fig. (3)**.

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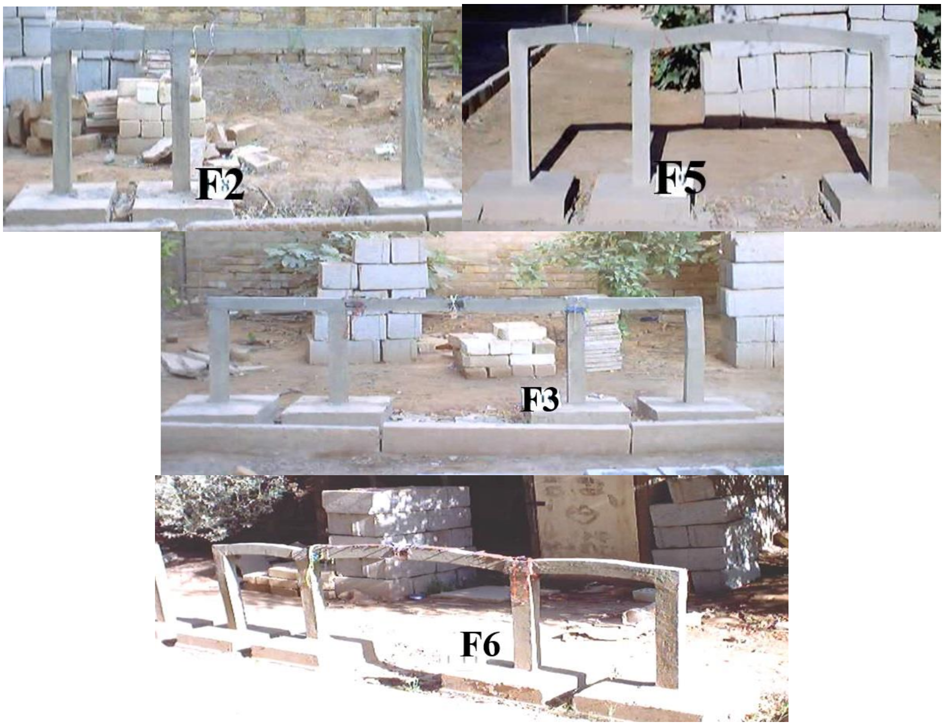
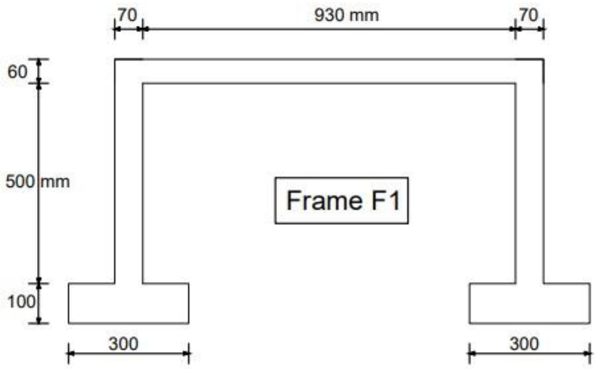
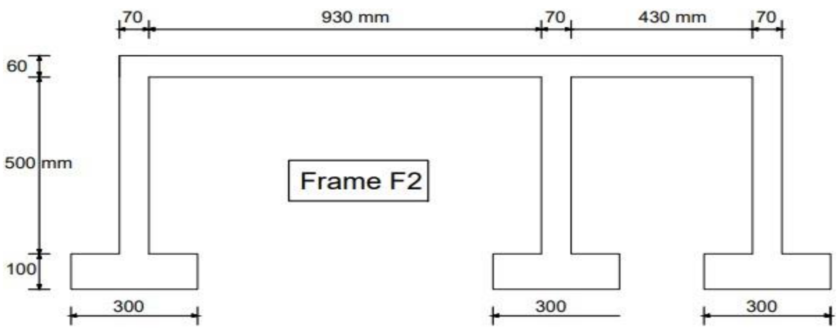


Figure (1) Models F1, F2, F3, F4, F5 and F6.





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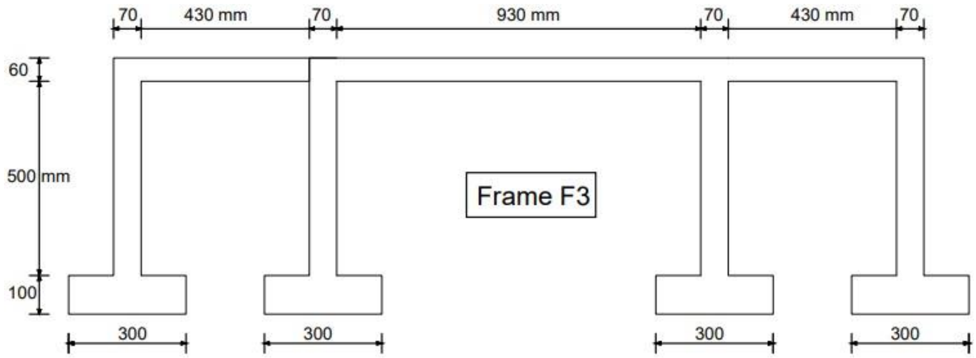

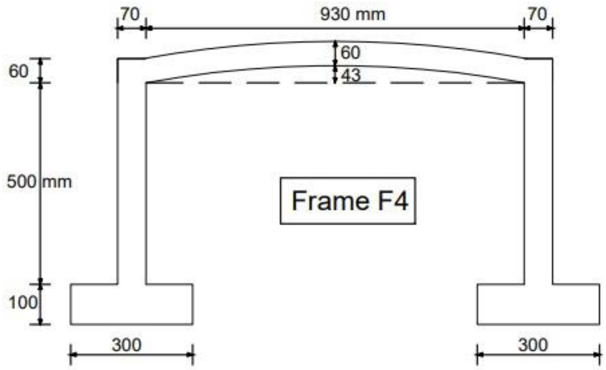

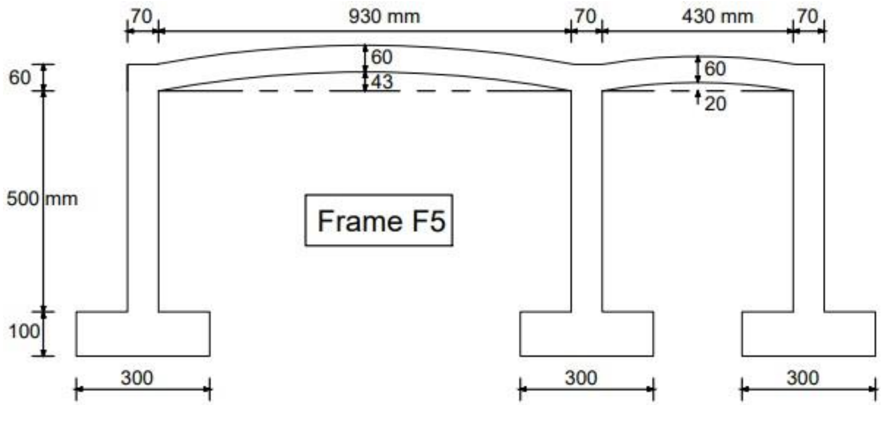

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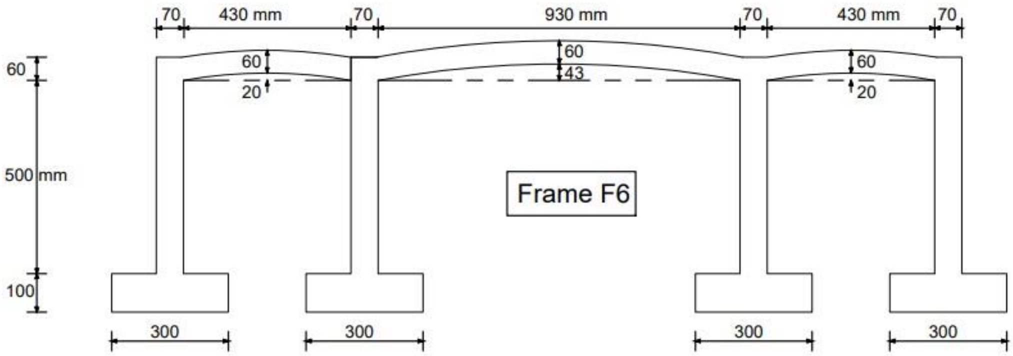

Figure (2) Geometrical details of models F1, F2, F3, F4, F5 and F6.

Load application samples

Failure mechanism and load scattering after Failure

Figure (3) Samples of load application and failure mechanism.

Generally, for uniformly loaded beams in portal frames, the shear force is maximum at both ends and minimum near mid-span. On the contrary, bending moment will be maximum at both ends and at mid-span, reducing to a minimum in between.

Weight of all above materials used as loading is measured before applying loading. Load is applied/increased gradually up until occurrence of failure mechanism which gives an indication to load capacity of six models, i.e. load bearing capacity is predicted to be the final weight of all meterials measured to load the beam. In other words, mathematical formulae are not used to predict load bearing capacity.

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Table 2 gives load capacity/failure load of models predicted experimentally and represented as uniform distributed load (UDL).

Table 2 Load capacity represented as UDL.

Model	No. of Spans	Beam Type	UDL (kN/m)
F1	Single	Straight	6.11
F4		Curved-up	6.64
F2	Double	Straight	10.87
F5		Curved-up	11.95
F3	Triple	Straight	13.46
F6		Curved-up	15.36

Discussion on Study Observations:

Experimental investigation gives rise to the following observations:

1. *Effect of Curved-Up on Load Capacity*

Considering load capacity results in **Table 2**, an enhancement to load capacity is observed in the range between 8.67% to 14.12%. This enhancement ratio is shown in **Table 3**. The average enhancement ratio can be taken as 11% due to the curved-up effect.

Table 3 Load capacity enhancement ratio.

Model	Beam Type	UDL (kN/m)	Enhancement
F1	Straight	6.11	8.67%
F4	Curved-up	6.64	
F2	Straight	10.87	9.94%
F5	Curved-up	11.95	
F3	Straight	13.46	14.12%
F6	Curved-up	15.36	
+ Ratio = [(15.36 – 13.46) / (13.46)] = 14.12%			

The ratio of the enhancement in load capacity can be represented as:

***Ratio of Enhancement in Load Capacity* = (11 ± 3)%** Eq. (1)

Above enhancement can be implemented on structural elements made of sustainable construction materials.

2. *Effect of Number of Spans on Load Capacity*

Results are taken for single-span beam, and for larger span of the double-span and triple span beams.

Table 4 provides enhancement ratio in load capacity for the above three span scenarios.

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Table 4 Load capacity enhancement ratio.

Models Compared	Beam Type	UDL (kN/m)		Enhancement
F1 (single) – F2 (double)	Straight	6.11	10.87	77.9%
F1 (single) – F3 (triple)	Straight	6.11	13.46	120.3% ++
F2 (double) – F3 (triple)	Straight	10.87	13.46	23.8%
F4 (single) – F5 (double)	Curved-up	6.64	11.95	78.0%
F4 (single) – F6 (triple)	Curved-up	6.64	15.36	131.3%
F5 (double) – F6 (triple)	Curved-up	11.95	15.36	28.5%

++ Ratio = [(13.46 – 6.11) / (6.11)] = 120.3%

The following can be concluded from **Table 4**:

1. Adding shorter span to one side of the single span beam model will enhance load capacity by 77.9% and 78.0% for both straight beam and curved-up beam models, respectively.
2. Adding shorter span on each side will enhance load capacity of interior span by 120.3% and 131.3% for both straight and curved-up beams.
3. Adding another shorter side span to the opposite side of existing shorter span for double-span model (i.e., making a double-span model as triple-span model), will enhance load capacity by 23.8% and 28.5% for the larger span of both straight and curved-up beam models, respectively.

Previous results prove that making interior span as a curved-up (cambered) beam will enhance load capacity of the beam.
The above enhancement can also be useful when using sustainable structural elements, reducing cost and improving novel building material development methods in resource-constrained and economically poor regions.

<u>Reason Behind Enhancement of Load Capacity:</u>

It is believed that introducing some shallow upward curvature to beams is mobilizing restraint forces. When the load is applied, a curved-up member tends to straighten. This tends to increase the length of a curved-up beam.
In trying to maintain original length, a horizontal axial force will be initiated at both ends due to restraining supports.

This axial restraining force increases the intensity of compressive stresses and decreases the intensity of tensile stresses across the concrete section. Such a stress field improves flexural performance and, as a result, load capacity will be enhanced.

Conclusion:

1. Straight and curved-up beams are investigated within three different models.
2. Models are single-span, double-span and triple-span models.

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3. Effect of curved-up beams is investigated compared to straight beams, both in similar models.
4. Experimental load is applied using non-mechanical/machine load application. This was by using and weighing different construction materials.
5. Load capacity enhancement due to curved-up beams ranges between 8.67% and 14.12% compared to straight beams.
6. For curved-up beams, load capacity enhancement due to a number of spans, ranges between 28.5% (changing from double-span into triple-span) to 78.0% (changing from single-span into double-span). The reason behind this is that adding a second span to a single curved-up beam enhances restraining action to the main span, hence mobilizing large value of axial force. On the other hand, adding another short side span to double-span beam will add less to the restraining action that is already mobilized due to first side span.
7. For straight beams, load capacity enhancement due to a number of spans ranges between 23.8% (changing from double-span into triple-span) to 77.9% (changing from single-span into double-span). Reason behind this is similar to that in point 6 above.
8. Changing single span beam into triple span beam enhances laod capacity by 120.3% for straight beams and 131.3% for curved-up beams because in straight beams, the load will deflect the straight beam. This deflection will equalize part of the restraining action and this will reduce axial action to be mobilized. On the contrary, in curved-up beams, this effect is minimized due to initial curved up. As a result, mobilized axial action will keep enhancing the restraining action.

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