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Parametric study of castellated beam with varying depth of web opening

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Abstract **-**Use of castellated beam for various structures rapidly gaining appeal. This is due to increased depth of section without any additional weight, high strength to weight ratio, their lower maintenance and painting cost. The principle advantage of castellated beam is increase in vertical bending stiffness, ease of service provision and attractive appearance.

However one consequence of presence of web opening is the development of various local effects. In this paper a steel section is selected, castellated beams are fabricated with increase in depth of web openings. Experimental testing is carried out on beam with two point load and simply supported condition. The deflection at centre of beam and various failure patterns are studied. The beams with increase in depth are then compared with each other and with parent section for various parameters and for serviceability criteria.

The widespread use of castellated steel beam as a structural member has prompted several investigation in their structural behavior. Castellated beams have proved to be efficient for moderately loaded longer spans where the design is controlled by deflection.

Index Terms- Castellated beam, Cellular beam, Web opening, Virendeel mechanism, Throat

I. Introduction

Engineers are constantly trying to improve the materials and practices of design and construction. One such improvement occurred in built-up structural members in the mid-1930, an engineer working in Argentina, Geoffrey Murray Boyd, is castellated beam. Castellated beams are such structural members, which are made by flame cutting a rolled beam along its centerline and then rejoining the two halves by welding so that the overall beam depth is increased by 50% for improved structural performance against bending. Since Second World War many attempts have been made by structural engineers to find new ways to decrease the cost of steel structures. Due to limitations on minimum allowable deflection, the high strength properties of structural steel cannot always be utilized to best advantage. As a result several new methods aimed at increasing stiffness of steel member, without any increase in weight of steel required. Castellated beam is one of the best solutions.

The responsibility of a Structural Engineer lies in not merely designing the structure based on safety and serviceability considerations but he also has to consider the functional requirements based on the use to which the structure is intended. While designing a power plant structure or a multi-storied building, the traditional structural steel framing consists of beams and girders with solid webs. These hinder the provision of pipelines and air conditioning ducts, electrical wiring required for satisfactory functioning for which the structure is put up.

The re-routing of services (or increasing the floor height at the design stage for accommodating them) leads to additional cost and is generally unacceptable. The provision of beams with web openings has become an acceptable engineering practice, and eliminates the probability of a service engineer cutting holes subsequently in inappropriate locations. Beams with web openings can be competitive in such cases, even though other alternatives to solid web beams such as stub girders, trusses etc are available. This form of construction maintains a smaller construction depth with placement of services within the girder depth, at the most appropriate locations. The introduction of an opening in the web of the beam alters the stress distribution within the member and also influences its collapse behavior.

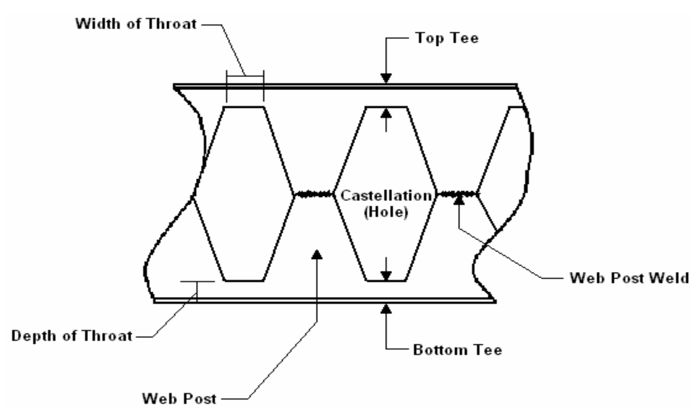


Fig.1 Terminology

- Web Post: The cross-section of the castellated beam where the section is assumed to be a solid cross-section.
- Throat Width: The length of the horizontal cut on the root beam. The length of the portion of the web that is included with the flanges.
- Throat Depth: The height of the portion of the web that connects to the flanges to form the tee section.

II. FORMULATION OF RESEARCH OBJECTIVES

For achieving economy, castellated beam fabricated from its parent solid webbed I section should have maximum depth. An available literature does not deal with the behavior of castellated beam with increase in depth of openings.

This paper investigates the effect of web openings on various structural aspects of castellated beam, various modes of failures, and effect on deflection with increase in the depth of web openings. Depth of beam increased in processes of castellation by 40, 50 and 60%, with hexagonal shape openings of angle 60^0. width, since the castellated beams are relatively slender and have web openings, which have an influence on their resistance. The major failure modes of castellated beams are web post buckling [2]-[3] and lateral-torsional buckling. The failure modes mainly depend on area of openings, location of opening, length of the tee-section above and below the opening, opening depth and type of opening, type of loading. The experimental testing on steel beams with web opening of various shapes and sizes is conducted.

Six potential failure modes [1] associated with castellated beams are-

A. Formation of Flexure Mechanism

This mode of failure can occur when a section is subject to pure bending. The span subjected to pure bending moment, the tee-sections above and below the holes yielded in a manner similar to that of a plain webbed beam, although the spread of yield towards the central axis was stopped by the presence of the holes by which time the two throat sections had become completely plastic in compression and in tension.

B. Lateral-Torsional Buckling

Non-composite castellated beams are more susceptible to lateral-torsional buckling than composite beams due to lack of lateral support to the compression flange. The lateral torsional buckling behaviour of castellated beams is similar to that of plain webbed beams. The holes had a significant influence on lateral-torsional buckling behavior.

C. Formation of Vierendeel Mechanism

Vierendeel bending is caused by the need to transfer the shear force across the opening to be consistent with the rate of change of bending moment, in the absence of local or overall instability, hexagonal castellated beams have two basic modes of plastic collapse, depending on the opening geometry. The failure is dependent on the presence of a shear force of high magnitude in the holes through span.

D. Rupture of the Welded Joint in a Web Post

Rupture of a welded joint in a web-post can result when the width of the web-post or length of welded joint is small. This mode of failure is caused by the action of the horizontal shearing force in the web-post, which is needed to balance the shear forces applied at the points of contra flexure at the ends of the upper I-section.

E. Shear Bucking of a Web Post

The horizontal shear force in the web-post is associated with double curvature bending over the height of the post. In castellated beam one inclined edge of the opening will be stressed in tension, and the opposite edge in compression and buckling will cause a twisting effect of the web post along its height.

III. EXPERIMENTAL TESTING

ISMB150 is selected as a parent section for fabricating castellated beam. Following guidelines are followed for fabrication-

- The hole should be centrally placed in the web and eccentricity of the opening is avoided as far as possible.
- Stiffened openings are not always appropriate, unless they are located in low shear and low bending moment regions.
- Web opening should be away from the support by at least twice the beam depth, D or 10% of the span, whichever is greater.
- The best location for the opening is within the middle third of the span.
- Clear Spacing between the openings should not be less than beam depth D.
- The best location for opening is where the shear force is the lowest.
- The diameter of circular openings is generally restricted to 0.5D.
- Depth of rectangular openings should not be greater than 0.5D and the length not greater than 1.5D for un-stiffened openings.
- The clear spacing between such openings should be at least equal the longer dimension of the opening.
- The depth of the rectangular openings should not be greater than 0.6D and the length not greater than 2D for stiffened openings. The above rule regarding spacing applies.
- Corners of rectangular openings should be rounded.
- Point loads should not be applied at less than D from side of the adjacent opening.
- If stiffeners are provided at the openings, the length of the welds should be sufficient to develop the full strength of the stiffener.
- If the above rules are followed, the additional deflection due to each opening may be taken as 3% of the mid-span deflection of the beam without the opening.

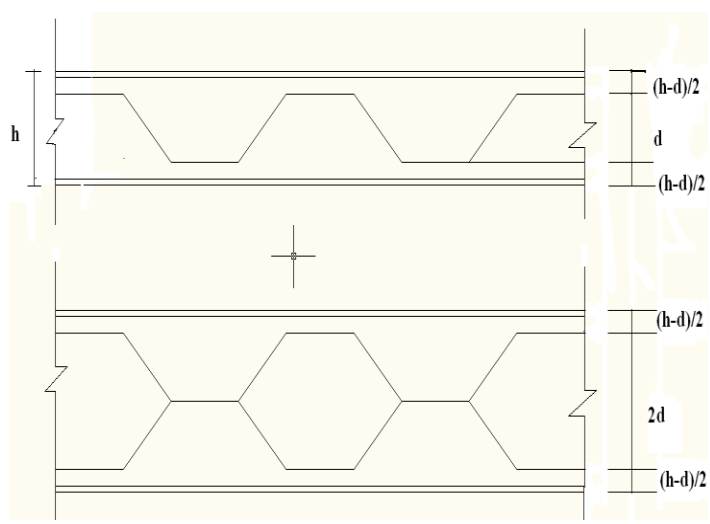


Fig.2 Mathematical Formulation of Castellated Beam

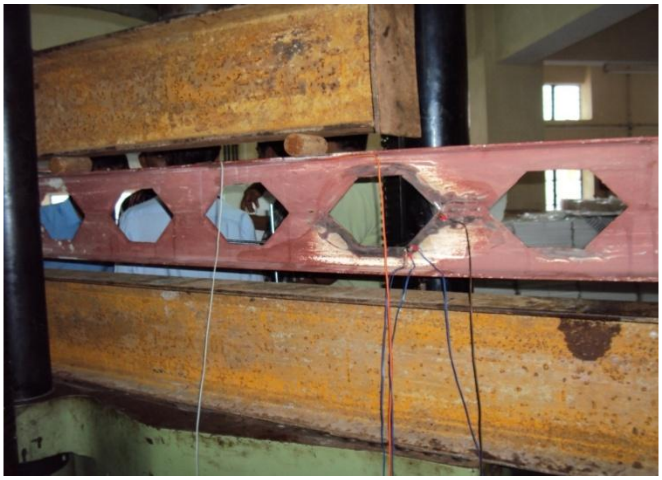


Fig.3 Beam Ic 210mm is Mounted of UTM for Testing

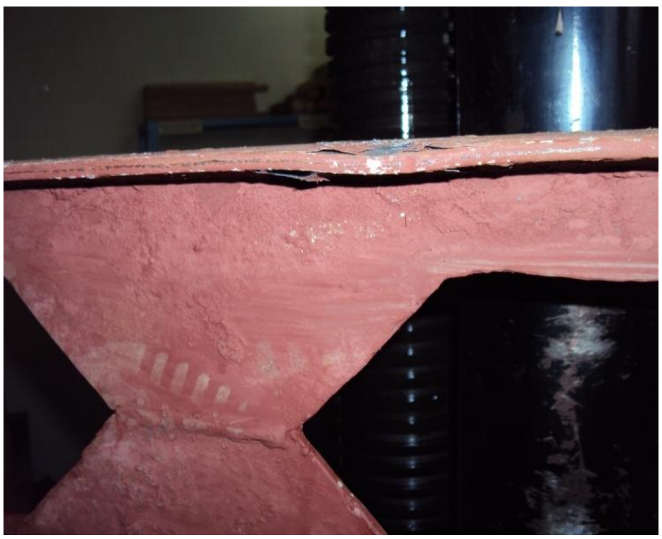


Fig.4 Local Failure Mode –Buckling of Compression Flange

Fig.5 Web Buckling of Beam Ic 225mm

Fig.6 Stress Concentration in Ic 225 at Hole Corner

Fig.7 Flexure Buckling of Beam Ic 240

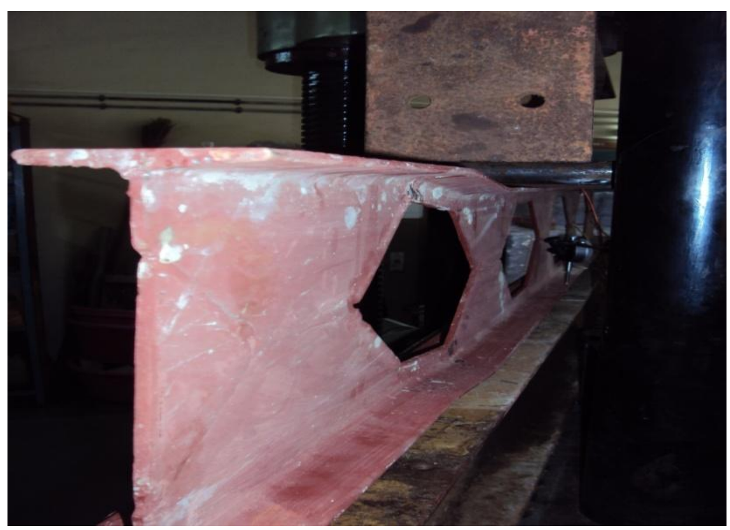


Fig.8 Failure of Beam Ic 240 In Flexure

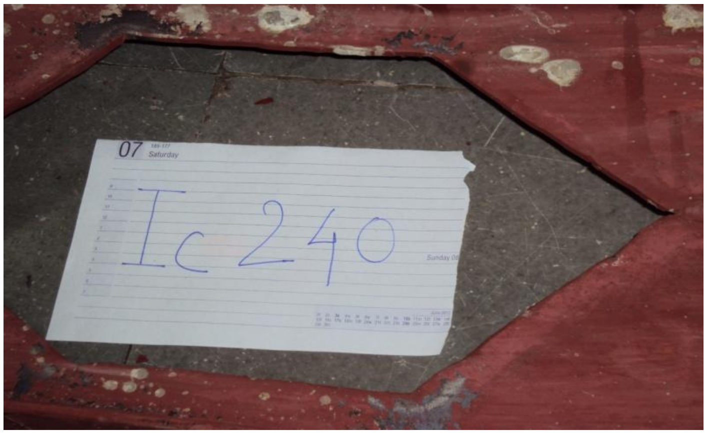


Fig.9 Local Failure -Vierendeel Effect (Stress Concentration at Hole Corners of IC 240)

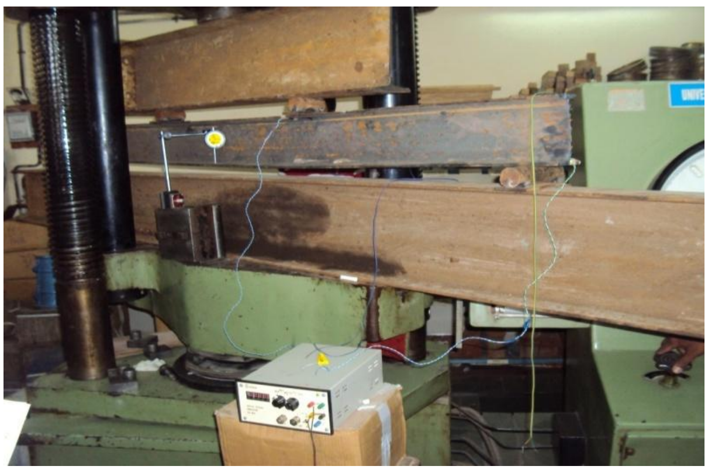


Fig.10 Testing Arrangement for Solid Web Beam ISMB 150

Fig.11 Local Failure- Failure of Compression Flange ISMB 150

Fig.12 Lateral Torsional Buckling of ISMB 150

IV. RESULTS

TableI: Load v/s Deflection for ISMB150

Sr. No.	Load (kN)	Deflection (mm)
1	0.00	0.00
2	10.38	0.82
3	20.38	1.50
4	30.38	2.60
5	40.38	3.54
6	50.38	4.40
7	60.38	5.50
8	70.38	6.25
9	80.38	7.15
10	90.38	8.00
11	100.38	9.30
12	110.38	12.35
13	112.38	18.58

Table II: Load v/s Deflection for Ic 210

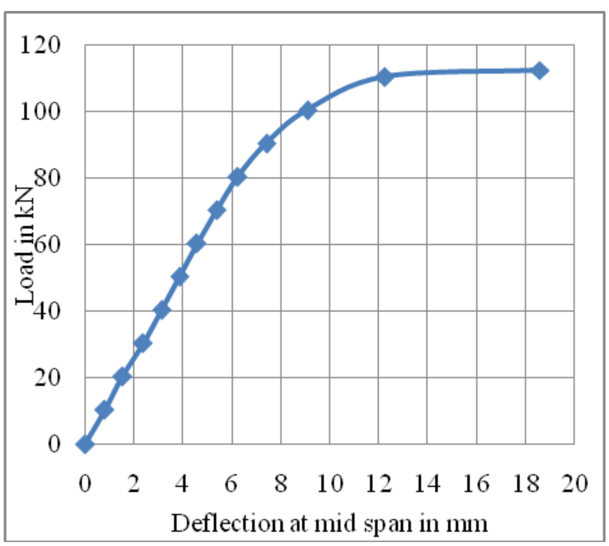
Sr. No.	Load (kN)	Deflection (mm)
1	0.00	0.00
2	10.38	1.00
3	20.38	1.70
4	30.38	2.54
5	40.38	3.45
6	50.38	4.50
7	60.38	5.40
8	70.38	6.42
9	80.38	7.32
10	90.38	8.55
11	94.38	9.45
12	96.38	10.54

Table III: Load v/s Deflection for Ic 225

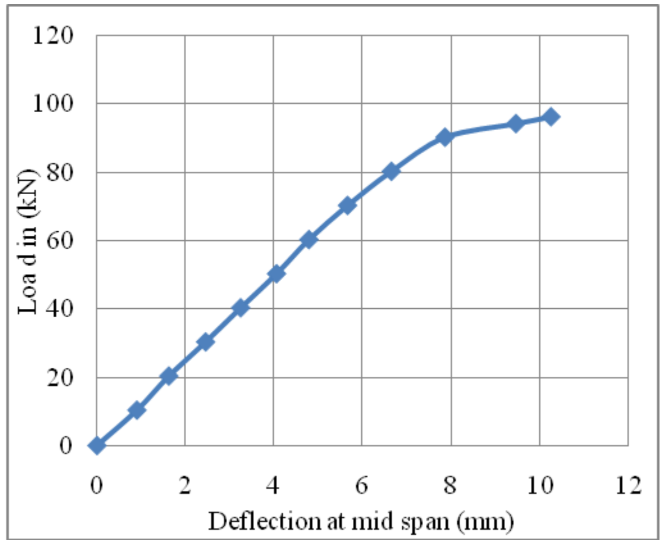
Sr. No.	Load (kN)	Deflection (mm)
1	0.00	0.00
2	10.38	0.90
3	20.38	1.70
4	30.38	2.56
5	40.38	3.48
6	50.38	4.55
7	60.38	5.56
8	70.38	6.87
9	80.38	9.22
10	90.38	12.6
11	94.38	13.93

Table IV: Load v/s Deflection for Ic240

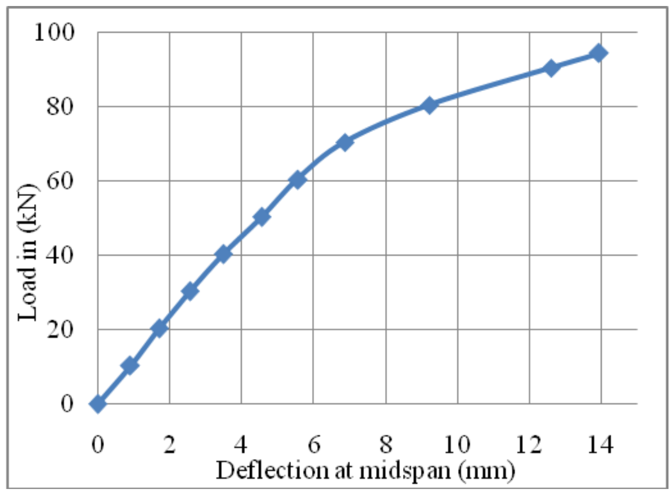
Sr No	Load (kN)	Deflection (mm)
1	0.00	0.00
2	10.38	0.72
3	20.38	1.61
4	30.38	2.55
5	40.38	3.48
6	50.38	4.50
7	60.38	5.81
8	70.38	8.72
9	80.38	16.00
10	84.38	20.76



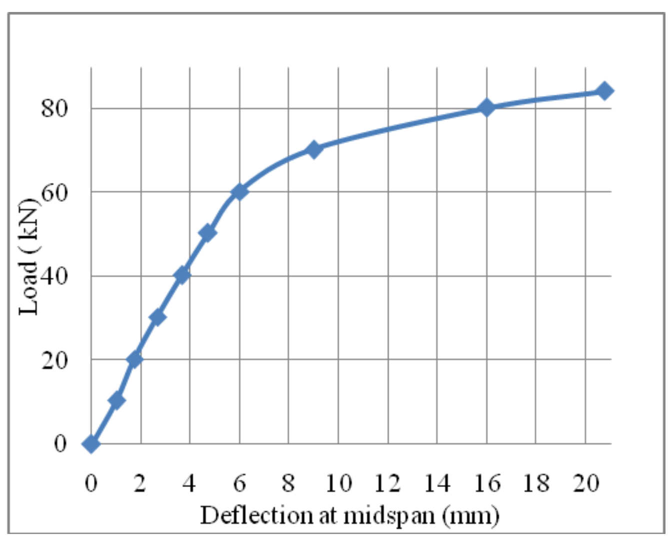
Graph.1 Load v/s Deflection for ISMB 150 by Testing



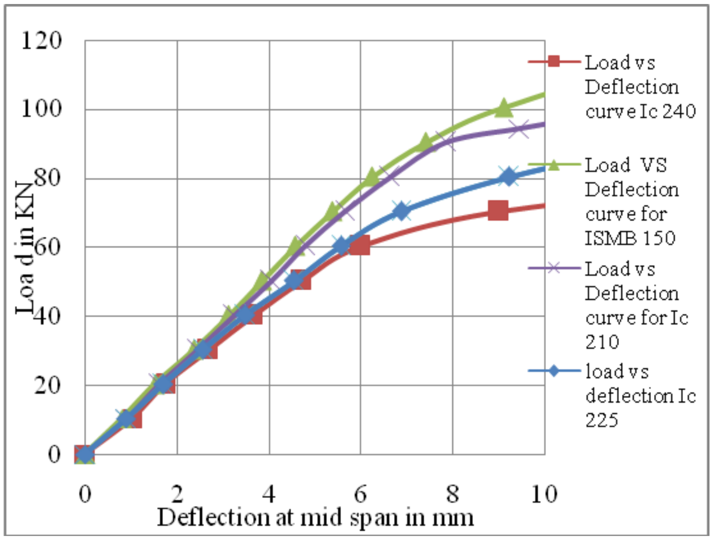
Graph.2 Load v/s Deflection for Ic 210 by Testing



Graph.3 Load v/s Deflection for Ic 225 by Testing



Graph.4 Load v/s Deflection for Ic 240 by Testing



Graph.5 Comparison of All Beam for Load v/s Deflection

Serviceability limit for beam= L/325=1900/325
=5.846mm

We can compare them for Serviceability limit, and the results are

TableV: Comparison of results for serviceability limit

Sr. No	Beam	Deflection (mm)	Max load (kN)	Local Mode Of Failure	Global Mode
1	ISMB 150	5.86	78	Failure of compression flange	Lateral torsional buckling
2	Ic 210		72	Failure of compression flange	Flexural buckling of Web
3	Ic 225		68	Failure of compression flange and Vierendeel effect	Web buckling
4	Ic 240		62	Vierendeel effect and Failure of compression flange	Flexural buckling of Web

This indicates that up to the serviceability limit castellated beams has nearly same stiffness of its parent beam. After this load increased continuously, due to presence of holes in the web opening it starts introducing some local effect, due to which its deflection increases rapidly and moment carrying capacity decreases. It also shows that beams castellated for 0.4D, 0.5D are showing good results where as beam castellated with 0.6D shows averaged result, that indicate some corrective measures should be taken to avoid this. For carrying maximum moment we have to follow following conditions while designing:

- To avoid local failure of beam. (i.e. provision of plate below concentrated load).
- To provide reinforcement at the weak sections of the beam.
- To avoid Vierendeel effect (to avoid stress concentration) corners of the holes are to be rounded.

V CONCLUSIONS

From the experimental testing, it is concluded that, Castellated steel beam behaves satisfactory for serviceability, up to maximum depth of opening 0.6D.

Castellated beams has holes in its web, as holes incorporated various local effects in beams, increase in load causes beams to be failed in different failure mode, which resist them to take load up to their actual carrying capacity. So we cannot compare beams with different modes of failure directly for strength criteria.

Due to the presence of holes in the web, the structural behavior of castellated steel beam will be different from that of the solid web beams. It make structure highly indeterminate, which may not analyzed by simple methods of analysis. So we have to design beam to avoid local effects, for improved performance of castellated beam. It is observed as depth of opening increases in Vierendeel effects is prominently observed at the hole corners, so by taking corrective measures (i.e corners should be rounded , provision of reinforcement) we can expect improvement in performance of beam.

We can conclude that castellated beams are well accepted for industrial buildings, power plant and multistoried structures, where generally loads are less and spans are more with its economy and satisfying serviceability criteria.

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