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BEHAVIOR OF REINFORCED CONCRETE BEAMS CONTAINING WASTE CRUSHED CONCRETE AND BRICKS

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Abstract

Recycling demolition waste materials as construction materials offers environmental as well as economic benefits by protecting virgin materials and reducing overall costs of project. This paper presents an experimental investigation on flexural behavior of reinforced concrete beams made with coarse aggregate fully 100 % or partially 50 % replaced by crushed concrete or crushed bricks as waste materials in full or half depth of beams. Nine beams are tested over a simply supported span, one with full natural aggregate as reference and the others with waste aggregate in different ratios and depths (four with crushed concrete and four with crushed bricks). Results show that the structural behavior of beams with waste aggregates is similar to the reference beam with strength reduction of 3 – 20 %. Crushed concrete beams show higher strength and stiffer behavior (in general) than crushed bricks. Also, increasing replacement ratio from 50 % to 100 % or replacement depth from half to full reduced strength by about 10 % only which encourage utilizing maximum quantity of waste construction materials in concrete structures.

Keywords:

Reinforced concrete beams;
Flexural behavior;
Crushed bricks;
Crushed concrete;
Coarse aggregate.

1 Introduction

Urban development and high growth rate in construction industries demand larger quantities of construction materials which in turn consumes natural resources. On the other hand, demolition waste is increasing and has become one of the most serious concerns worldwide [1-3]. So, recycling waste materials in constructions offers environmental as well as economic benefits such as reducing extraction of virgin materials and overall projects costs [2, 4-6].

Since concrete is the most common construction material and about 75 % of concrete volume is occupied by aggregate, waste materials like crushed concrete and/or crushed bricks have successfully used as coarse and/or fine aggregate in various percentages to produce new concretes even though they, generally; give lower strength and stiffness than conventional concrete [7-12]. However, studies show that less or no negative effect is observed when the ratio of waste aggregate is about 50 % or less [1, 8, 13].

Malešev et al. 2010 [14] and Kumutha and Vijai 2010 [8] stated that the use of waste aggregate concrete, even with 100 % replacement of natural aggregate, is possible and mainly satisfactory. Furthermore, there is no negative impact on compressive, flexural and splitting strengths of concrete if waste aggregate of good quality is used regardless of the replacement percentage [14]. McNeil and Kang 2013 [15] reported that although replacing natural aggregate by waste aggregate reduces compressive strength, it gives equivalent or higher splitting tensile strength. Similar conclusion is reached by Silva et al. 2021 [3].

Bashandy et al. 2017 [9] showed that using waste aggregate (crushed concrete and crushed granite) may yield sufficient strength for self-curing high-strength concrete.

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In structural level, waste aggregate is shown to be an appropriate alternative to natural aggregate in concrete for buildings [11, 16].

Many researchers found that the flexural strength of reinforced concrete beams with different replacement ratios of waste aggregate is equivalent to or even greater than that of natural aggregate beams where failure is still governed by main steel yielding [10,15,17-20]. Other researchers recorded lower capacity for beams with waste aggregate compared to natural aggregate beams [3, 5, 11, 12, 21].

Cracking pattern and deflection response of beams containing waste aggregate are similar to those of natural aggregate concrete beams as reported by Malešev et al. 2010 [14]; Seara-Paz et al 2018 [18]; Wang et al. 2019 [21]; Oad et al. 2019 [4]. However, some researchers indicated that deflection is greater and cracks are more and closer in waste aggregate beams due to lower modulus of elasticity and higher shrinkage, respectively [5, 11, 12, 17, 19].

2 Objective of this work

As mentioned before, exploiting waste materials in construction industry offers environmental and economic benefits. It can be concluded from the above literature review that the results are somewhat contradictory. Also, using waste aggregate in part of the beam was not covered. The main objective of this work is to experimentally investigate structural influence of using local waste materials (crushed concrete or crushed bricks) as full or partial replacement of coarse aggregate in full or half depth of reinforced concrete beams.

3 Experimental work

To achieve the objective of this work, nine reinforced concrete beams were cast and tested in flexure. Concretes containing crushed concrete or crushed bricks as coarse aggregate were used either in the full beam or only in the tension zone. Details of experimental procedure are presented in the following sections.

3.1 Materials

The materials used in this investigation are:

- Ordinary Portland cement satisfying Iraqi standard specification No.5-1984 [22].
- Fine aggregate (sand) and coarse aggregate (natural gravel, crushed concrete and crushed bricks, Fig. 1) with nominal maximum size of 10 and 20 mm, respectively; satisfying Iraqi Standard Specification No. 45-1984 [23]. Crushed concrete and bricks are gotten by crushing tested/broken laboratory concrete and brick samples then removing all contaminations.
- Tap water for aggregate washing, concrete mixing and curing of specimens.
- Steel reinforcement: Ø 12 mm (deformed) with yield strength of 532 MPa for tension and Ø 8 mm (deformed) with yield strength of 428 MPa for shear in all beams. Also, Ø 6 mm smooth bars were used at top to hold stirrups in positions.



Fig. 1: Used coarse aggregate: natural gravel (top), crushed concrete (left) and crushed bricks (right).

3.2 Concrete mixes

In order to obtain the most suitable mixes, several trials were done. Mix proportions listed in Table 1 were used in this work where differences are the contents of coarse aggregate types (natural gravel, crushed concrete and crushed bricks). Concrete mixes are either contain coarse aggregate of one type 100 % or two types, 50 % each, as shown in Table 1. The water/cement ratio was 0.52 % for all mixes.

Table 1: Proportions of concrete mixes.

Mix	Portion of cement	Portion of sand	Portion of natural gravel	Portion of crushed concrete	Portion of crushed brick
G100	1	1.5	2.8	-	-
C100	1	1.5	-	2.8	-
B100	1	1.5	-	-	2.8
C50	1	1.5	1.4	1.4	-
B50	1	1.5	1.4	-	1.4

3.3 Mixing and casting

A horizontal rotary mixer was used to mix concrete in a conventional procedure where coarse aggregate and sand mixed first for about 2 minutes. In mixes containing two types of coarse aggregate, they premixed well before adding sand. Then cement was supplied and the dry ingredients were mixed for 3 minutes to get a homogeneous dry mix, then water was added and mixing continued until achieving a homogeneous mixture. All fine and coarse aggregates were used in a saturated-surface dry state.

After cleaning molds, oiling their inner surfaces and fastening parts, steel reinforcements were put in their places in the mold, Fig. 2.

Full depth (one layer) beams were cast by pouring the specific concrete continuously into molds and compacted using a vibrating table.

For hybrid beams, bottom layer was placed and compacted first (which is different from beam to other), then the top layer (which is made of mix G100) was placed and compacted after about 30 minutes from placing the first layer.

Three cubes 100 × 100 × 100 mm and three cylinders 100 × 200 mm were cast with each mix to determine compressive and splitting tensile strengths, respectively.

After 24 hours, all specimens were demolded and cured in water until age of 28 days.



Fig. 2: Mold and reinforcement.

3.4 Designation and details of beams

Nine reinforced concrete beams of dimensions 100 × 200 × 1100 mm were tested in flexure in this work. Five beams are fully cast using single concrete mix (one for each mix in Table 1) and four as two layers beams (hybrid) with equal thickness (half depth) for each layer. Concrete mixes with coarse aggregate fully or partially replaced by crushed concrete or crushed bricks were used in tension

(bottom layer) while reference mix with natural gravel G100 was used in compression (top layers) as shown in Fig. 3.

Each beam is designated using two letters and one number: letter F or H refers to full depth (one layer) or hybrid (two layers) beam, respectively. Letter G, C or B refers to coarse aggregate type (natural gravel, crushed concrete or crushed bricks, respectively. Number 100 or 50 refers to the replacement ratio of the specified aggregate 100 % or 50 %, respectively, Fig. 3. For example, beam FC100 is a one-layer beam fully made of mix C100 (coarse aggregate are 100 % crushed concrete), while beam HB50 is a two layers beam with top layer made of mix G100 (coarse aggregate are 100 % natural gravel) and bottom layer made of mix B50 (coarse aggregate are 50 % natural gravel and 50 % crushed bricks).

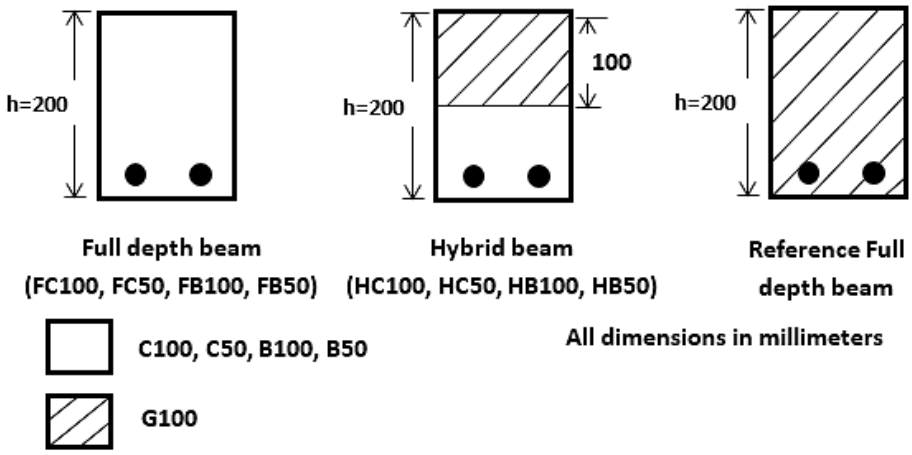


Fig. 3: Types of the tested beams.

All beams were tested over a simply supported span of 1000 mm (roller supports) and longitudinal and transverse reinforcement were kept the same (2Ø12 mm and 8 mm at 70 mm, respectively) as shown in Fig. 4.

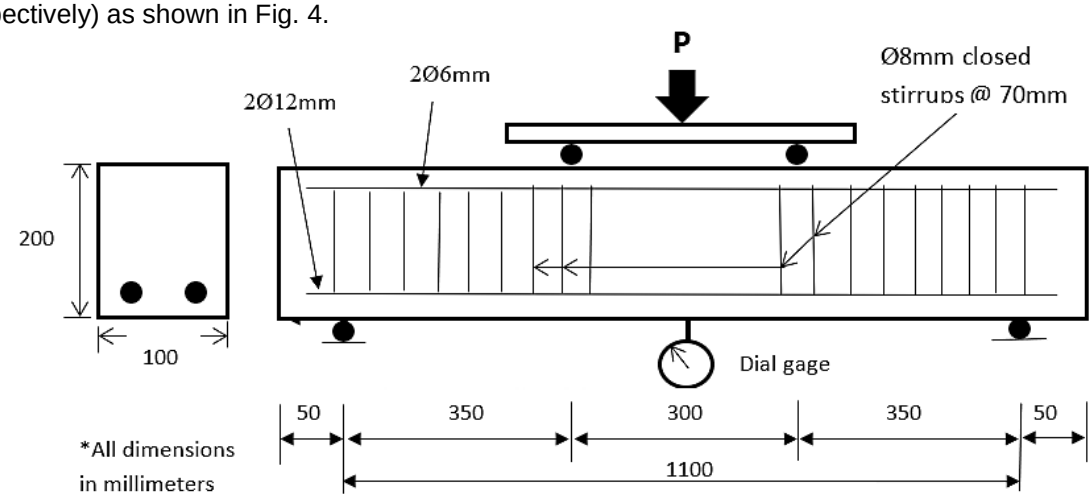


Fig. 4: Details of the tested beams.

4 Test results

4.1 Compressive and tensile strengths

Cubes (100 × 100 × 100 mm) and cylinders (100 × 200 mm) were tested according to BS EN 12390-3:2019 [24] and ASTM C496/C496M-11 [25] to determine compressive and splitting tensile strengths using a compression machine of 2000 kN capacity and a hydraulic testing machine of 50 kN capacity, respectively. The results shown in Table 2 reveal that concrete with natural gravel has higher strength than those contained crushed concrete or bricks as coarse aggregate. This is expected since natural gravel is stiffer than these waste aggregates. Results also show that using crushed concrete as aggregate gives higher compressive strength 89 – 97 % of compressive strength of natural gravel

concrete, than crushed bricks 75 – 86 %. Corresponding ratios for splitting tensile strength are 70 – 96 % for crushed concrete and 55 – 80 % for crushed bricks. Finally, partial replacement 50 % of natural gravel by either crushed concrete or crushed bricks is better in terms of strength than full replacement 100 %.

Table 2: Results of compressive and tensile strengths

Mix	Compressive strength f_{cu} [MPa]	Tensile strength f_t [MPa]
G100	36	2.86
B100	27	1.56
B50	31	2.29
C100	32	2.01
C50	35	2.75

4.2 Testing and results beams

All beams were tested in flexure over a simply supported span of 1000 mm, Fig. 5 under a monotonically increased static loading (by force) up to failure using a universal hydraulic testing machine of 3000 kN capacity. The load was applied gradually in small increments. The vertical mid-span deflection was measured every 5 kN using mechanical dial gauge of 0.01 mm accuracy. Crack development and propagation were monitored and marked during the progress of the test. Failure modes of the tested beams were also noticed.



Fig. 5: A beam under test.

4.3 Structural behavior, cracking pattern and failure mode

Generally, structural behavior of the tested beams is similar where at first, several cracks initiated in the bottom face at the maximum moment portion between the two-point loads with nearly uniform spacing among cracks.

With continued loading, these cracks widened and propagated upwards while new cracks appeared in the neighboring shear spans. Further loading led to fast propagation and widening of one (or more) of the cracks in the middle progressing to the compression zone. Finally, the beam failed by yielding of longitudinal reinforcement companied by excessive deflection and followed by crushing of compression concrete as shown in Fig. 6. Maximum crack width ranges, generally; between 1.5 mm and 2.8 mm. Cracks in beams with crushed concrete or crushed bricks were relatively more and spacings were smaller than in reference beam.

No signs of debonding, interface cracks or separation were observed between concrete layers in hybrid beams.



Fig. 6: Cracking patterns and failure modes.

4.4 Failure loads

Table 3 show results of flexure tests on beams. As shown in this table and Fig. 7, using crushed concrete or crushed bricks to fully or partially replace natural gravel in full or half depth of reinforced concrete beams reduces their strength by about 3 – 20 %. However, this reduction range can be considered acceptable taking into account the environmental and economic benefits acquired from using waste materials instead of natural ones.

Table 3: Test results of beams.

Beam	Layers	Coarse aggregates		Failure load *P* [kN]	*P/P* (Ref.) [%]	Maximum deflection [mm]	Maximum crack width [mm]
FG100 (Ref.)	One	100 % Gravel		126	100	6.2	2.75
FB100	One	100 % Crushed brick		102	80.95	5.5	1.50
FB50	One	50 % Gravel + 50 % Crushed brick		114	90.48	6.1	1.90
HB100	Two	Top layer	100 % Gravel	115	91.27	5.1	2.00
		Bot. layer	100 % Crushed brick				
HB50	Two	Top layer	100 % Gravel	101	80.16	4.9	2.80
		Bot. layer	50 % Gravel + 50 % Crushed brick				
FC100	One	100 % Crushed concrete		112	88.89	5.9	1.85
FC50	One	50 % Gravel + 50 % Crushed concrete		123	97.62	5.2	1.90
HC100	Two	Top layer	100 % Gravel	103	81.75	6.2	1.55
		Bot. layer	100 % Crushed concrete				
HC50	Two	Top layer	100 % Gravel	108	85.71	4.8	1.95
		Bot. layer	50 % Gravel + 50 % Crushed concrete				

- **Type of coarse aggregate:** In general, beams with crushed concrete have slightly higher failure loads 81.75 - 97.62 % of reference beam, than those with crushed bricks 80.16 - 91.27 %. This is a result of that crushed concrete particles which already contain natural coarse aggregate is stronger than crushed bricks.
- **Replacement ratio:** Increasing replacement ratio from 50 % to 100 % decreases flexural strength by about 9 % for full depth replacement for both crushed concrete (beams FC50 and FC100) and crushed bricks (beams FB50 and FB100). For hybrid beams with crushed concrete, the decreasing is only 4 % (beams HC50 and HC100) while inverse response (strength increase) is recorded for hybrid beams with crushed bricks (beams HB50 and HB100). These results encourage exploiting waste demolishing materials to the widest range in concrete structures by fully replacing natural gravel.
- **Replacement depth:** Generally, for the same replacement ratio; failure loads of full depth replacement (one layer) beams are higher (7 - 12 %) than those for half depth replacement (two layers) beams (beams FB100 and HB100 are an exception). This behavior can be attributed to the more integrity of one-layer beams as compared to the two layers (hybrid) beams. This supports full depth replacement instead of half depth to avoid integrity and practical problems while utilizing maximum quantity of waste construction materials.

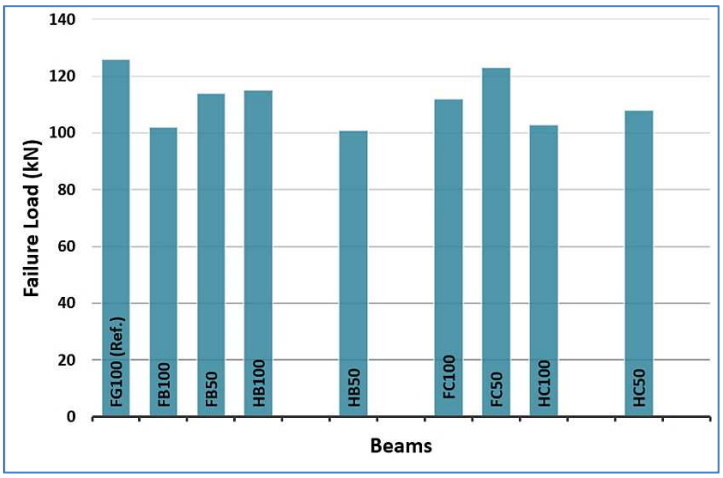


Fig. 7: Failure loads of the tested beams.

4.5 Load – deflection response

Figs. 8 to 11 show load-deflection behavior for the different groups of the tested beams. Generally, the behavior is elastic (linear load-deflection response) in the first phase until cracks in the

tension face initiated and developed causing curvature of the curve to change into a less steep with increasing deflection. Continued propagation of flexural cracks crossing the compression zone leads to a ductile failure mechanism with semi-flat curve (higher deflections under lower load increments) until failure.

Maximum mid-span deflections at failure of all beams are comparable and ranged from 4.8 mm to 6.2 mm as listed in Table 3.

Figure 8 illustrates that reference beam with 100 % natural gravel FG100 show stiffer response (lower deflection) than other full depth replacement beams followed by beams with 50 % replacement ratio FC50 and FB50 then beams with 100 % replacement ratio FC100 and FB100. This is because natural gravel is stiffer than crushed concrete and crushed bricks.

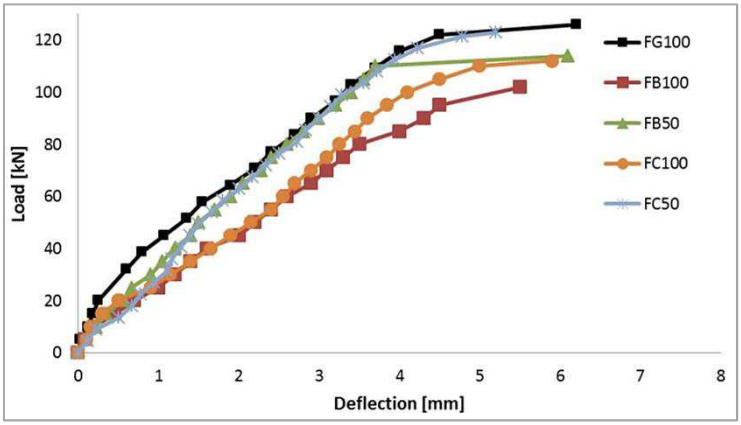


Fig. 8: Load – deflection curves for beams with full depth replacement.

Load-deflection behaviors are seemed to be convergent for hybrid (two layers) beams, crushed brick beams and crushed concrete beams as shown in Fig. 9, 10 and 11, respectively. This assures the effectiveness of using waste demolishing aggregates in concrete beams to replace natural aggregate without negatively affecting their behavior.

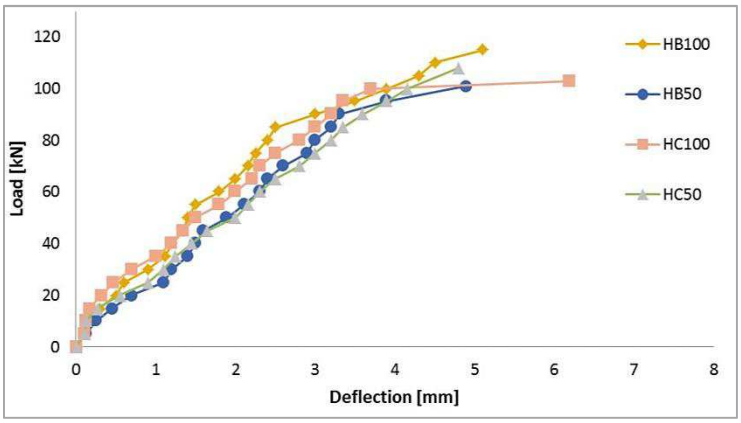


Fig. 9: Load – deflection curves for beams with half depth replacement.

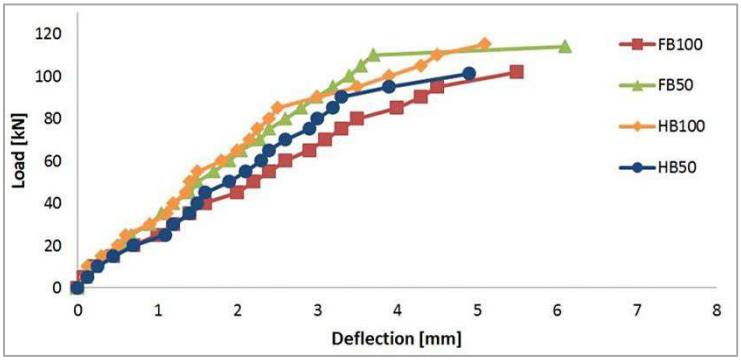


Fig. 10: Load – deflection curves for beams with crushed bricks.

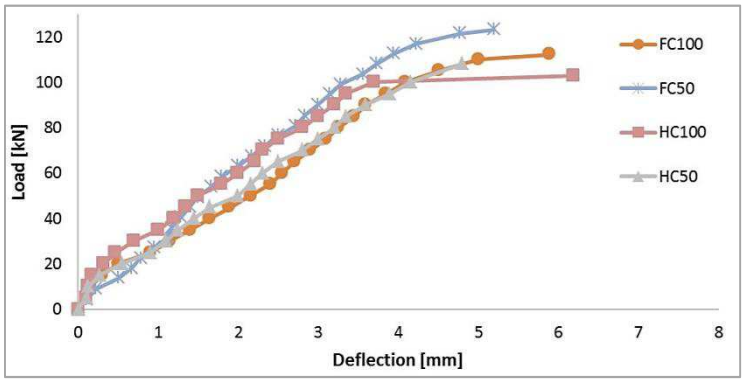


Fig. 11: Load – deflection curves for beams with crushed concrete.

5 Conclusions and recommendations

From the results of the experimental investigation conducted in this work, several conclusions and recommendations may be stated:

1) Using waste materials like crushed concrete and crushed bricks (separately) as coarse aggregate to fully 100 % or partially 50 % replace natural gravel in concrete gives compressive strength (compared to reference full gravel concrete) of 89 – 97 % and 75 – 86 %, respectively. Corresponding ratios for splitting tensile strength are 70 – 96 % for crushed concrete and 55 – 80 % for crushed bricks.

2) Structural behavior of all beams is similar and using crushed concrete or crushed bricks to fully or partially replace natural gravel in full or half depth of reinforced concrete beams reduces their strength by about 3 – 20 %. This reduction can be considered acceptable taking into account the environmental and economic benefits acquired from using waste materials instead of natural ones.

3) Beams with crushed concrete have slightly higher failure loads 81.75 - 97.62 % of reference beam, than those with crushed bricks 80.16 - 91.27 %.

4) Increasing replacement ratio from 50 % to 100 % decreases flexural strength by about 9 % or less. These results encourage exploiting waste demolishing materials to the widest range in concrete structures by fully replacing natural gravel.

5) Generally, for the same replacement ratio; failure loads of one-layer beams are higher 7 - 12 % than those for two layers beams. This supports full depth replacement instead of half depth to avoid integrity and practical problems while utilizing maximum quantity of waste construction materials.

6) Load-deflection responses of all tested beams are, generally; convergent with slight stiffer behavior of reference beam (lower deflection).

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