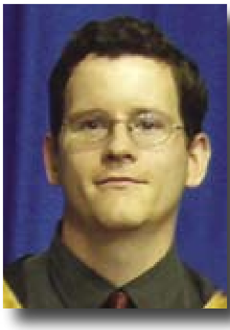
Bearing Capacity of Grouted and Ungrouted Recessed Ends in Hollow-Core Slabs



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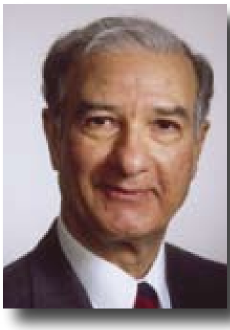

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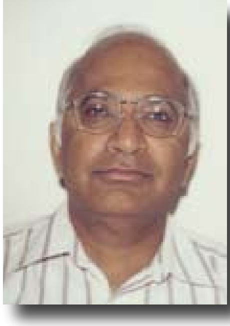

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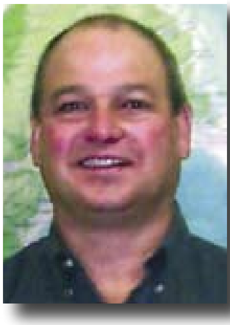

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This article is presented as an initial investigation into the feasibility of using recessed ends in hollow-core slab construction. It is found that in many practical situations, hollow-core slabs with recessed ends are needed on the job site. Experimental and finite element studies are conducted to determine the stress distribution in grouted and ungrouted recessed ends of hollow-core slabs. The current design procedure followed is also outlined. General observations and recommendations for design are provided. To illustrate the design procedure, a numerical design example is included.

Hollow-core slabs are quickly replacing traditional cast-in-place flooring systems on many job sites. One important consideration exists when designing these members specifically; because these units are precast in a plant, they must be designed to accommodate site conditions.

In some situations, hollow-core slabs are required to have one or both of their end(s) supported at a location(s) were the available height is less than the overall depth of the slab. To solve this problem, it is proposed herein to use a recessed end. This involves removing a given depth of the slab (from the top side, as shown in Fig. 1) over the length of the obstruction. Having removed this depth of material, stress concentrations can be expected to form at the location of sudden depth change, and also the shear capacity at the end of the slab will decrease.

Therefore, in an attempt to compensate for any reduction in the member's shear strength capacity, it is suggested that grout be added to this region after the recess is formed. This

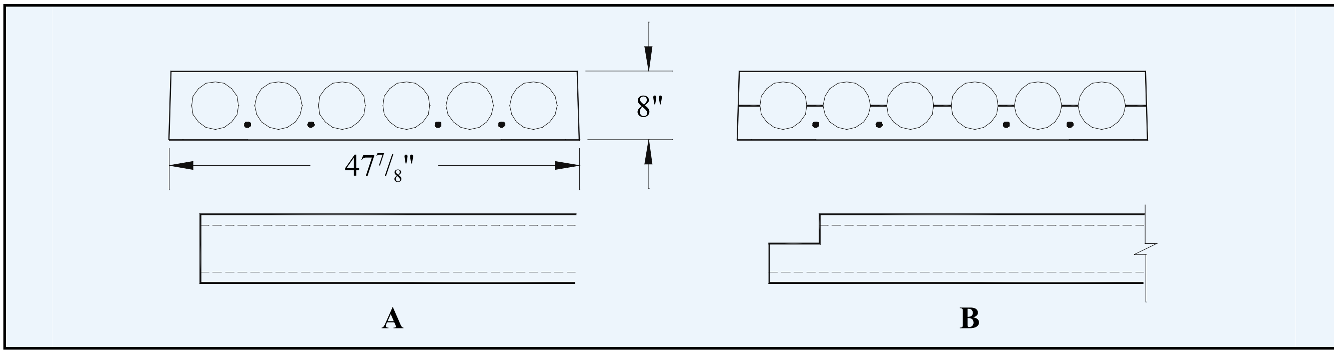

Fig. 1. Schematics of hollow-core slab. (A) No recess, (B) Recessed. Note: 1 in. = 25.4 mm.

additional grout fills the voids and makes a solid section in the recessed zone. But before this can be done in practice, it is important to examine the feasibility of employing such modifications.

A review of current literature has revealed that no information relative to the shear capacity of such modified ends exists. The focus of this paper is to examine the effect of end modifications (in the form of recessed ends) on the strength capacity of hollow-core slabs, including the effect of adding grout to the modified region. The effects of these modifications are examined both experimentally and analytically.

DESIGN CONSIDERATIONS

Currently, the procedure for designing hollow-core slabs with recessed ends differs little from that used for standard hollow-core members. The only factor that significantly changes is the shear resistance of the member, as a result of the change in slab depth. The nominal shear strength V_c of the hollow-core slab can be determined from either of the following two codes (CAN/CSA A23.3-94[1] or ACI 318-99[2]).

CAN/CSA A23.3-94

(i) $$V_c = 0.2\lambda\phi_c\sqrt{f_c'}b_w d \quad \text{(defining the lower limit)} \tag{1}$$

$$V_c = 0.06\lambda\phi_c\sqrt{f_c'}b_w d + \frac{V_f}{M_f}M_{cr} \tag{2}$$

where
- f_c' = specified compressive strength of concrete
- λ = factor based on concrete unit weight (=1.0 for normal weight concrete)
- b_w = width of section
- d = effective depth of section
- ϕ_c = resistance factor for concrete (0.65 for precast concrete)
- V_f = factored shear strength
- M_f = factored moment
- M_{cr} = cracking moment

The cracking moment is defined as:

$$M_{cr} = \left(\frac{I_g}{y_t}\right)\left(0.6\lambda\phi_c\sqrt{f_c'} + \phi_p f_{ce}\right) \tag{3}$$

where
- I_g = gross moment of inertia of section
- y_t = distance from neutral axis to extreme fiber in tension
- f_{ce} = effective stress in concrete
- ϕ_p = resistance factor for prestressing tendon (0.90)

The shear resistance of the section's web is defined as:

$$V_{cw} = 0.4\lambda\phi_c\sqrt{f_c'}\sqrt{1 + \frac{\phi_p f_{cp}}{0.4\lambda\phi_c\sqrt{f_c'}}}b_w d + \phi_p V_p \tag{4}$$

where
- V_p = shear resistance due to prestressing force
- f_{cp} = stress in concrete due to prestressing force

The above equations are listed in CAN/CSA A23.3-94.[1]

It should be noted that Eq. (2) relates to a section's capacity to resist flexural shear failure whereas Eq. (4) is used to determine the section's capacity to resist web shear failure. Furthermore, V_c shall not exceed V_{cw}.

ACI 318-99

(ii) $$V_c = \left(0.6\sqrt{f_c'} + 700\frac{V_u d}{M_u}\right)b_w d \tag{5}$$

or the lesser of:

$$V_c = 0.6\sqrt{f_c'}b_w d + V_d + \frac{V_i M_{cr}}{M_{max}} \tag{6}$$

where

$$M_{cr} = \left(\frac{I}{y_t}\right)\left(6\sqrt{f_c'} + f_{pe} - f_d\right) \tag{7}$$

or

$$V_{cw} = \left(3.5\sqrt{f_c'} + 0.3 f_{pc}\right)b_w d \tag{8}$$

where V_c shall not be less than:

$$V_c = 1.7\sqrt{f_c'}b_w d \tag{9}$$

Equations (5) through (8) are taken from ACI 318-99.[2]

EFFECT OF RECESSED ENDS

For both the Canadian and American codes, the effective depth d does not have to be taken as less than $0.8h$ for prestressed concrete members [with the exception of Eqs. (2) and (5)] because of flexural implications in the equations. When applying the previously cited equations to hollow-core slabs with recessed ends, the only variables that change are d and the associated cross-sectional properties.

In the case where the recessed end is grouted, the previous method is currently used to determine conservatively the approximate shear capacity of the hollow-core slab; the grout is considered absent. Therefore, there is currently no additional strength associated with grouting recessed ends. While it is assumed that the grout is effective in transferring stresses, its beneficial effects are neglected to be conservative.

Using the formulas and guidelines provided by CAN/CSA A23.3-94[1] [Eqs. (1) through (4)], an analysis was performed to determine the shear capacity of a full depth member and three different members with recessed ends. The calculations yielded the shear resistance envelopes, shown in Fig. 2, and provided an image of the critical section in the region around the bearing area.

In all cases, it was found that the shear distribution due to loading intercepted the shear resistance envelopes in the region corresponding to the transfer length of the prestressing strand. The results of these calculations show that the maximum load that the member can carry prior to shear failure is constant, irrespective of the presence of a recess. However, the results indicate that at the abrupt change in the cross section, a sudden change in the shear strength is observed, as would be expected.

In hollow-core slabs without recessed ends, a compression strut will form at the location of the support. By modifying the ends of the hollow-core slab, this beneficial effect, while not completely eliminated, may be reduced. By reducing the depth of the cross section in the bearing region, the critical shear value may lie closer than anticipated to the edge of the support.

For those unfamiliar with recessed-end slabs, concern often arises over the stresses acting at the change in cross-sectional area. The stresses in this region are nonlinear due to the sudden cross-sectional change. This nonlinearity spans a distance equal to approximately h (in which h is the depth of the section), along the member's length (based on St. Venant's principle).

In this zone, the stresses in the extreme fibers will be amplified by some factor. Due to this amplification, it can be anticipated that cracks will form at much lower applied loads. As the cracks increase in size, with increasing load, the ability of the cross section to transfer shear across the crack will be significantly reduced.

Consider a hollow-core product with recessed ends when the voids (cores) at the end(s) are filled with concrete. This concrete fill, while often of a different strength, forms a solid cross section. The addition of the concrete in the core area increases the cross-sectional properties (such as moment of inertia and cross-sectional area) and, therefore, will help to reduce the stresses in this critical zone. However, if the fill is only placed in the recessed area, additional stress concentrations may form. The stresses in the fill concrete will have to transfer into the hollow-core slab concrete within the recessed region.

EXPERIMENTAL STUDY

Eight hollow-core slabs were manufactured using a standard procedure with a zero slump concrete and an automated casting system. After a casting bed of product was manufactured, the fresh (modifiable) concrete was marked with special details and cut lines. In situations where a recessed end was required, the location was marked.

While the concrete was still in a workable state, it was removed from the recessed area, down to the required depth. The recess was then filled with grout to compensate for the removed materials. Grout added at this stage had a compressive strength of about 3500 psi (25 MPa), compared to the 6000 psi (41.4 MPa) used to form the hollow-core slab itself.

The slabs all had a depth of 8 in. (200 mm), a width of 47 7/8 in. (1216 mm), and a total length of 12 ft (3600 mm). Referring to Fig. 3, each hollow-core slab was simply supported, along its entire width, over a clear span distance of 8 ft (2440 mm). This allowed one end of the hollow-core slab to extend past the support by a distance of approximately 4 ft (1220 mm).

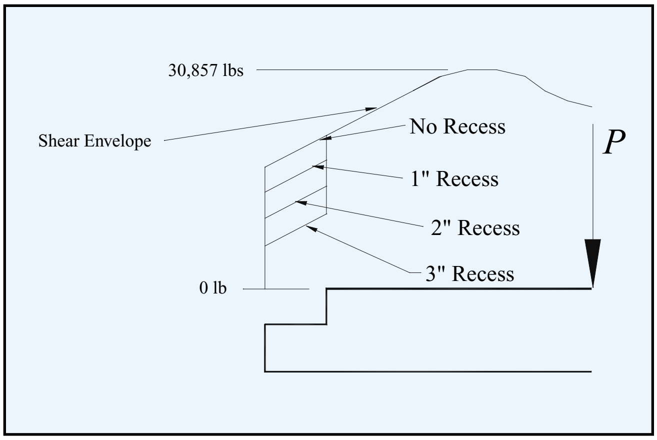

Fig. 2. Schematic of shear envelope for all recess cases. Note: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

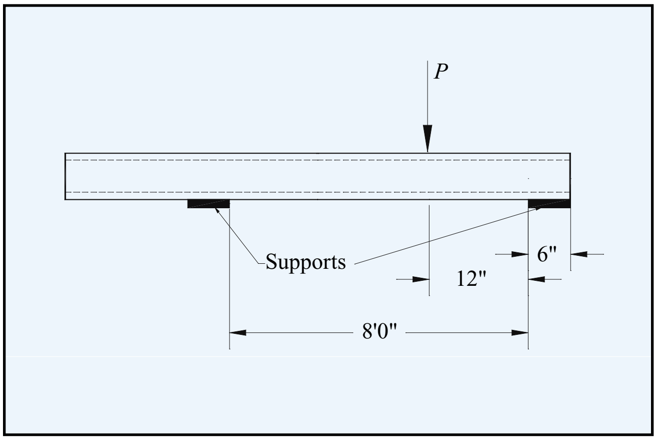

Fig. 3. Experimental setup. Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m.

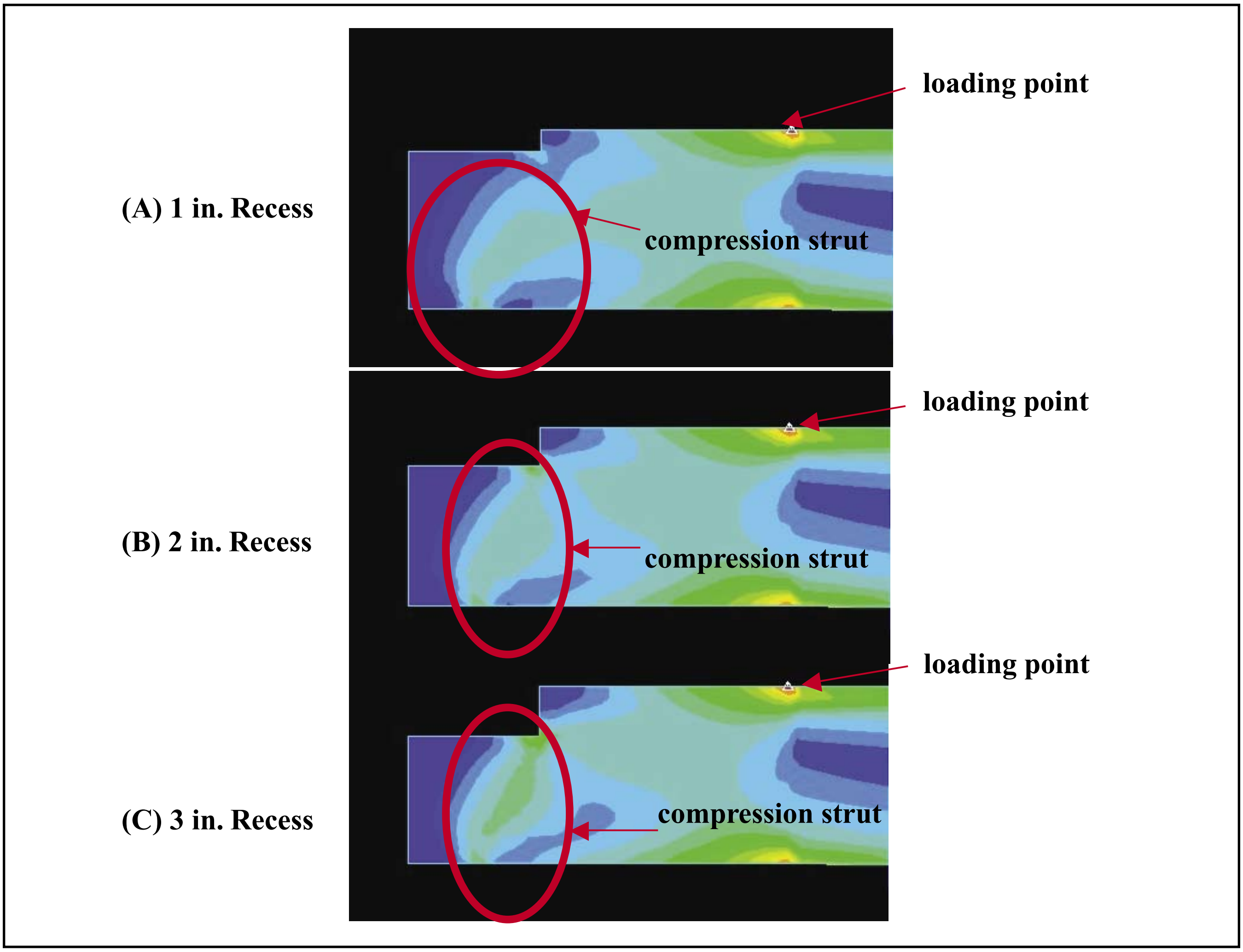

Fig. 4. Effect of recessing on effective stress distribution along hollow-core slab. Note: 1 in. = 25.4 mm.

The reason for this cantilever was to protect the slab end from any damage, thereby making it available for further testing. A load, distributed across the member's width, was placed 12 in. (300 mm) from the edge of the support (at the non-cantilevered end).

It was anticipated that the compression zone (due to the method of support commonly found in the field) at the bearing end will span a distance of up to $h/2$ (where h is the slab thickness) away from the edge of the support. Moreover, a compression zone will form under the load itself, spanning an assumed distance of $h/2$. The 12 in. (305 mm) distance for load placement was chosen to avoid the convergence of these two compression zones.

The following four hollow-core slab geometries were tested for both the grouted and ungrouted case:

(a) No recess (full depth section);
(b) 1 in. (25.4 mm) recess (Case A);
(c) 2 in. (51 mm) recess (Case B); and
(d) 3 in. (76 mm) recess (Case C).

In all the previous cases, the bearing length, and thus the length of the recess, was restricted to 6 in. (150 mm) as shown in Fig. 3. Also, each of the above conditions was tested twice to provide an average.

FINITE ELEMENT STUDY

A finite element analysis (FEA) of the studied cases was undertaken using the ADINA-AUI software.[4] This analysis was done to determine the stresses developed in the member during loading. The main body of concrete was modeled using three-dimensional, eight-node solids throughout the member.

The properties entered for the concrete materials conformed to the design values of f'_c = 6000 psi (41.4 MPa) and a triaxial failure curve for the concrete (defined within ADINA-AUI).[4] The prestressing strand was defined as a multilinear plastic material and was entered into the software such that it conformed to the curve given in the PCI Manual for the Design of Hollow Core Slabs.[5] For the purpose of modeling, the prestressing strands were modeled using reinforcing bar elements subjected to an initial strain of 0.00556. This strain was based on the anticipated effective prestressing strain.

The load applied to the member was kept constant, at approximately 50 percent of the ultimate design value, and was evenly distributed across the width of the member. It was assumed that the member was simply supported in each case, with the boundary conditions imposed at a distance of 3 in. (76 mm) from the ends of the member, which was the center of bearing.

For the grouted cases, the grout was modeled in an identical manner to that of the hollow-core slab concrete; its compressive strength was taken as 3500 psi (25 MPa).

DISCUSSION OF RESULTS

The FEA study was used to investigate the internal mechanics involved in the transfer of load through the recessed ends of the hollow-core slabs to the bearing support. Fig. 4 provides a profile of the stresses in the region of the bearing end for the three hollow-core slab cases with recessed ends.

Referring to Fig. 4(a), a distinct stress distribution can be seen extending from the center of the bearing region out towards the applied load, which represents the compression strut. For the slab with the 2 in. (51 mm) recessed end [see Fig. 4(b)], this compression region shifts back towards the edge of the recess. For the 3 in. (76 mm) recessed case [see Fig. 4(c)], the compression strut does not shift back towards the recessed edge, but it still intersects the edge of the recess, amplifying stress levels.

The results from the FEA indicated that the stress distribution in the region of a recess is improved significantly by the presence of a grouting material. However, while the stresses in the recessed end experience an improved distribution pattern in the presence of grout, the stress magnitude is intensified.

The results also showed that the presence of a recess reduces the load necessary for first crack formation, a situation supported by the laboratory findings. Moreover, it was also found that the introduction of the grout helped the member rebound from this first crack load to some degree.

The results for all the cases revealed that the maximum tensile stress in the member occurred in the region of the load, at the outside edge of the member and at the extreme fiber (as expected). The presence or absence of grouting, or the presence of a recess, did not affect this result.

When comparing the full depth grouted and ungrouted sections, an important observation was made. It was found that the introduction of the grout into the bearing region resulted in a reduction in the maximum tensile stress of 12 psi (83 kPa), suggesting a better stress distribution mechanism.

It should be noted, however, that cracks formed at much lower loading values as the recess depth increased. From the FEA it was observed that, for the ungrouted cases and under 50 percent of the ultimate load, the maximum tensile stress increased (compared with a section with no recess) by 2, 4.8, and 19.7 psi (14, 33, and 136 kPa) for a 1, 2, and 3 in. (25.4, 51, and 76 mm) recess, respectively.

When comparing the grouted section, a similar increase in tensile stresses was observed. These increases were 1.2, 3, and 5.5 psi (8.3, 20.7, 38 kPa) for the 1, 2, and 3 in. (25.4, 51, and 76 mm) recesses, respectively, compared to the full depth section. Note that the effect of the recess is not as significant for the grouted cases as it was in the ungrouted cases.

Table 1 summarizes the results of the experimental testing. For each recess depth, the ultimate loads are listed. The ultimate loads listed are an average of the results from two specimens for each case.

In every experimentally tested case, the ultimate load of the specimen was greater than the values obtained from the design formulas [Eqs. (1), (2), and (4)].

Comparing the values in Table 1, there is an approximately 9 to 16 percent increase in ultimate load due to grouting. This beneficial effect associated with grouting increases with increasing recess depth. A statistical "t" test showed the differences in the ultimate loads in Table 1 are significant (at the 2 percent level of significance).

For the tested specimens, the formation of the initial crack occurred at progressively lower load values as the recess depth was increased. This trend was supported by the results of the FEA.

In each specimen, the prestressing tendons began to slip from the ends due to increasing crack size as the ultimate load was approached. Cracks also formed in the region around the tendons. This type of cracking was only observed in the laboratory (the FEA was limited to loads below the cracking load). However, the results from the FEA did show substantial stress increases in the region around the tendons as the load increased, thereby suggesting that this region may crack first, thus producing a situation associated with the loss of bond.

In all the tested specimens, the failure surface was consistent with a flexural shear failure, as shown in Fig. 5. Results from the FEA agreed with this conclusion because the predominate stresses in the specimens suggest a strong potential for flexural shear failure.

Furthermore, all the tested specimens developed their initial crack at the outer bottom edge of the member, in the region next to the load application site. This result also agreed with the findings from the FEA, which suggest that the maximum tensile stress in the member developed in this region.

Table 1. Ultimate load sustained for four different recess depth cases.

Recess depth (in.)	**Ultimate load (lb)**		**Difference (lb)**
	No grout	**With grout**	
0	42,240	45,700	3460
1	35,740	39,400	3660
2	34,160	40,110	5950
3	34,080	39,340	5260

Note: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

CONCLUSIONS

Based on this study of grouted and non-grouted recessed ends in hollow-core slabs, the following conclusions may be drawn:

1. Existing design equations provide conservative values for hollow-core slabs without recessed ends.
2. The depth of a hollow-core slab's recessed end influences the profile of the compression strut developed near the loaded ends of slabs.
3. Grouting of the recessed end of a hollow-core slab tends to increase the slab's ultimate load capacity.
4. While recessed ends tend to reduce the cracking moment of the hollow-core slabs, grouting of the recessed ends have the opposite effect, thus preventing premature cracking.

Further work is suggested to examine the effects of various slab depths, compressive strengths of concrete material and grout, and the prestressing force.

To illustrate the design procedure, a numerical design example is included in Appendix B.

ACKNOWLEDGMENTS

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3. *CPCI Design Manual—Precast and Prestressed Concrete*, Third Edition, Canadian Prestressed Concrete Institute, Ottawa, Ontario, Canada, 1996.
4. ADINA– Automatic Dynamic Incremental Non-Linear Analysis, ADINA R & D Inc., Watertown, MA, Copyright 1994-2002, 2004.
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APPENDIX A—NOTATION

b_w = minimum effective web width within depth d
d = distance from extreme fiber in compression to centroid of longitudinal reinforcement
f'_c = specified compressive strength of concrete
f_{ce} = effective stress in concrete
f_{pc} = stress in concrete due to prestressing force
f_{pe} = effective stress in prestressing tendons after prestress losses
h = height (thickness) of slab/member
I = moment of inertia of section
I_g = gross moment of inertia of section

Fig. 5. Typical failure in hollow-core slab.

M_{cr} = cracking moment
M_u = factored moment at given section
M_{max} = maximum moment in section
M_n = factored moment resistance at given section
V_c = shear capacity of concrete
V_{cw} = shear capacity of web
V_f = factored shear strength
V_n = factored shear resistance at given section
V_p = shear resistance due to prestressing force
V_u = factored shear force at given section
y_t = distance from neutral axis to extreme fiber in tension
λ = factor based on concrete unit weight (for the current work, $\lambda = 1.0$ for normal weight concrete)
ϕ_c = resistance factor for concrete (0.65 for precast concrete)
ϕ_p = resistance factor for prestressing tendons (0.90)

APPENDIX B—DESIGN EXAMPLE

The following numerical design example is based on a recent hollow-core slab project for an office building in Ohio, for which the first author was the precast designer. The 12 in. (305 mm) thick hollow-core slabs were specified by the structural engineer to have a minimum bearing length of 4 in. (102 mm).

Based on the available angle and the requirement for a recess (also specified by the engineer) the bearing length was approximately 6 in. (152 mm) long (as was the case in the laboratory) after detailing was complete. Fig. B1 provides the developed detail, from the project shop drawings.

The following analysis was conducted for a member with and without a recess to demonstrate the calculated differences.

The following information is known:
Design code: ACI 318-99
Superimposed live load = 100 psf
Superimposed dead load = 9 psf
Self-weight and topping (2 in. structural) = 74 psf + 25 psf
Span = 39 ft 4 in.
Specified concrete compressive strength = 6000 psi

The following hollow-core slab properties are known:
(Note that all slabs are 48 in. wide)
For the full depth section:
Moment of inertia = 7868 $in.^4$
Cross-sectional area = 350.1 $in.^2$
Height = 12 in.

For slabs with a 2 in. recess (no core filling):
Moment of inertia = 2087 $in.^4$
Cross-sectional area = 199.4 $in.^2$
Thickness = 10 in.
Note: 1 psf = 0.4788 kPa; 1 ft = 0.3048 m; 1 in. = 25.4 mm.

Using the formulas presented in this paper (by means of the Concise Beam software), and assuming the support acted in the center of the recess, the shear force diagrams found in Figs. B2 and B3 were generated for the unrecessed and recessed section, respectively.

Note that for the recessed section, the structural topping was not extended into the recess zone. From the shear force diagram, some differences can be observed near the recess zone; however, the overall performance of the member does not appear to be impaired, as was found in the laboratory study. Moreover, there was not a significant calculated reduction in the system's strength capacity in the recess zone.

While the topping was not extended into the recess zone, it must be realized that the majority of cases requiring a recess will have some amount of concrete topping. During the application of the topping, the recess zone would fill solid with the topping material. If consideration of the topping filling any formed void is given, the need for core filling at the fabrication stage is not necessary, as the section exhibits sufficient strength for construction stage loading. Any hesitation, which may be developed about the suitability of the recess under the service condition, would not be realized with post-topping.

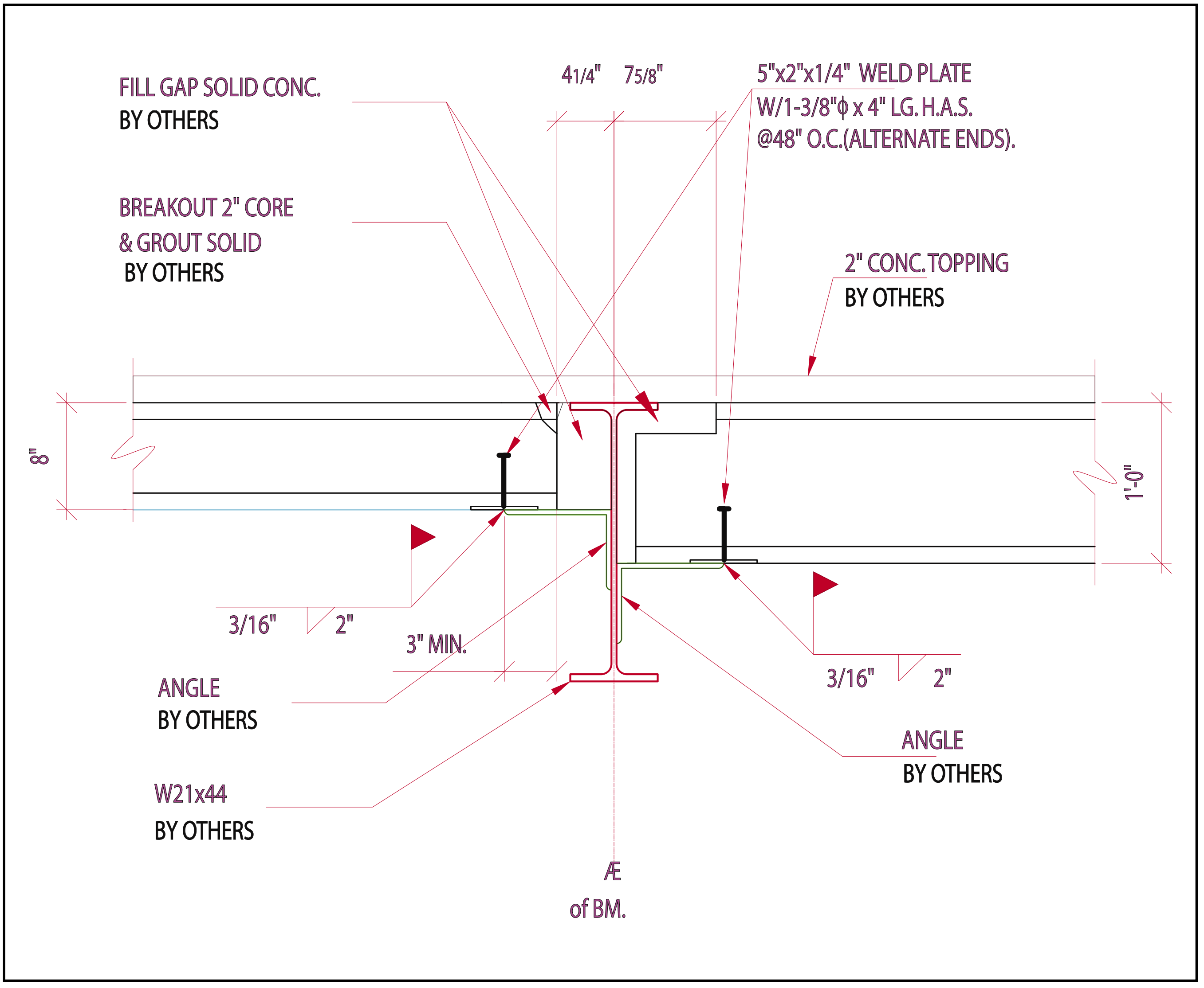

Fig. B1. Diagram associated with numerical design example (from an existing project). Note: 1 in. = 25.4 mm.

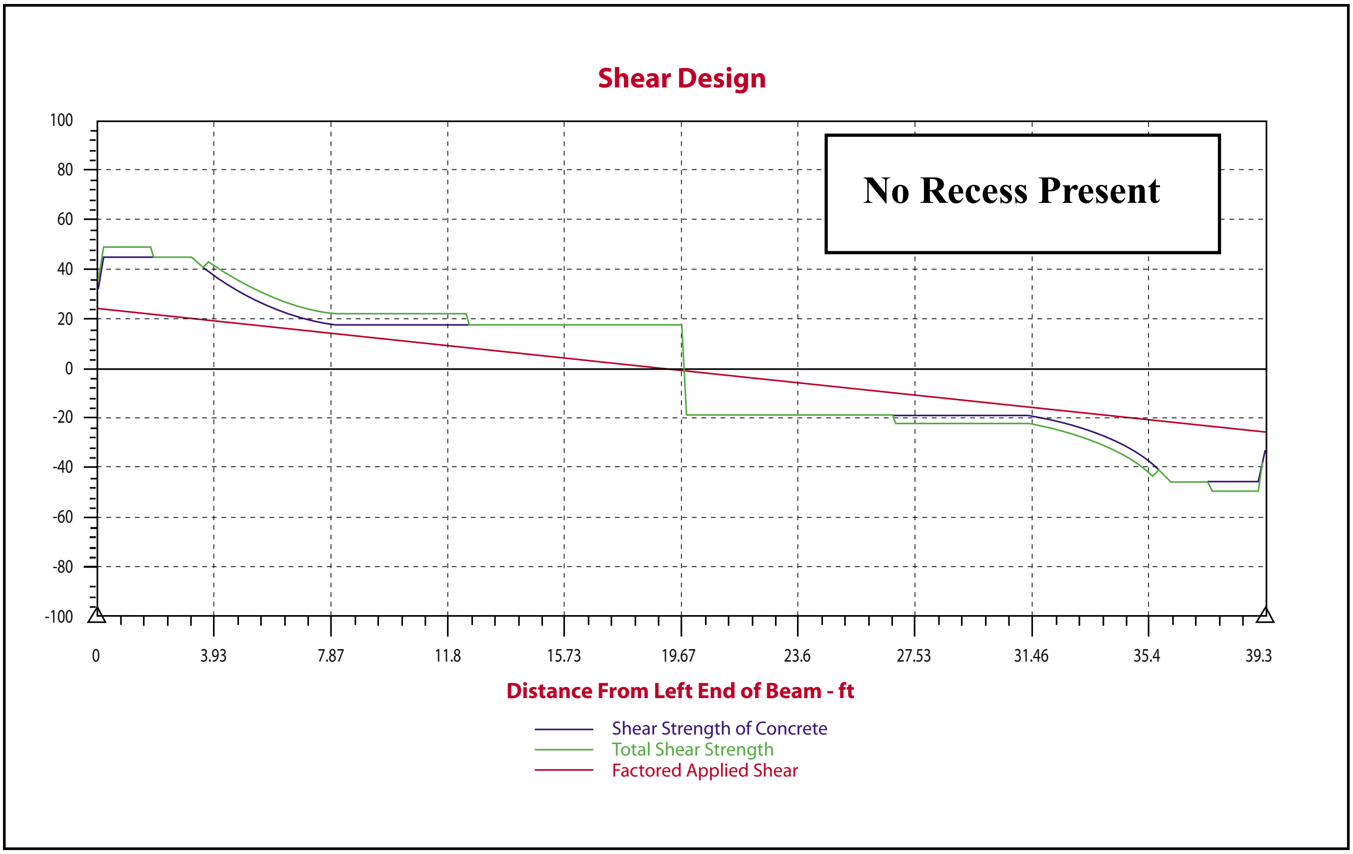

Fig. B2. Shear force diagram (produced by Concise computer program) for the hollow-core slabs without a recess.
Note: 1 ft = 0.3048 m.

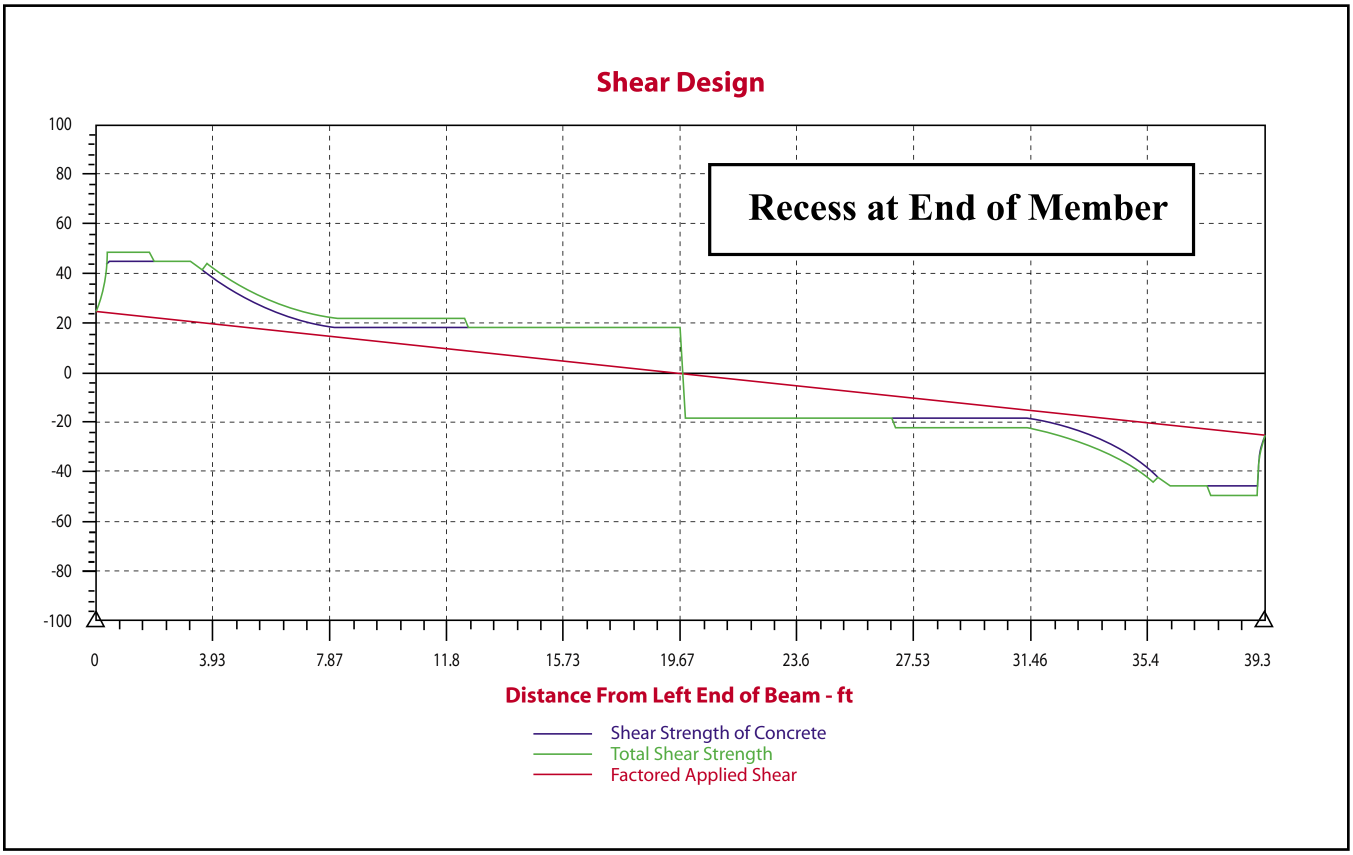

Fig. B3. Shear force diagram (produced by Concise computer program) for hollow-core slabs with a 2 in. recess.
Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm.