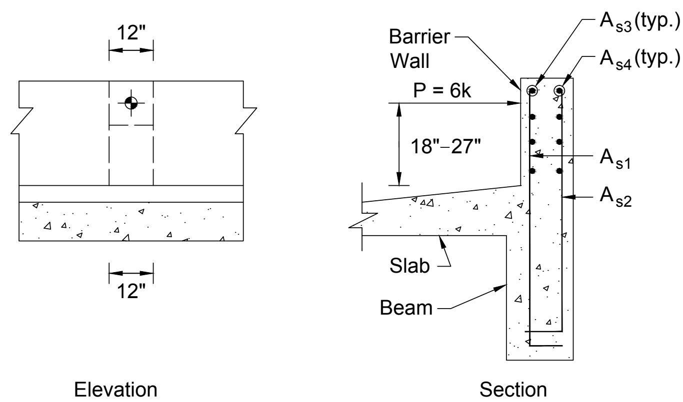

Figure 1. Load assumed to be resisted by 1-foot width of the wall.

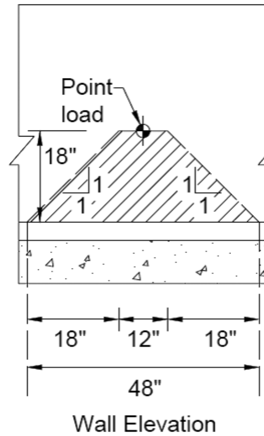

Figure 2. Distribute-and-Spread scheme for a single load.

Design of Vehicular Barrier Walls

ASCE 7-10 Requirements

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The perimeter of parking garages, and the edges of split ramps in the interior of parking garages, are required to have barriers, restraints or guardrails to stop the vehicles inside the structure from plunging down. The design and detailing of the perimeter walls has been a concern to public safety. The author has published three articles in STRUCTURE magazine on the subject calling for a rational design method for vehicular barrier systems. The first two articles presented a method on how to calculate the impact load on rigid and linearly elastic barrier systems. It was shown that the magnitude of the vehicular impact force depends on four factors: mass, speed, crushing characteristics of the vehicle, and barrier stiffness. It was also shown that the code-prescribed load to design the barriers was unreasonable and arbitrarily set too low, and that there was a need for a rational approach to design the vehicular barriers. The third article discussed the deficiency in the wall-slab joint, which causes cantilever concrete barrier walls to fail prematurely. The scope of this article is limited to the barrier walls. The article reviews the code requirements for design of the barrier walls using language of the current code, and provides suggestions on analysis and design of the walls. Specifically, it addresses the provisions of section 4.5.3 of ASCE 7-10 *Minimum Design Loads for Buildings and Other Structures* which prescribes the loads on vehicle barrier systems:

> ***4.5.3 Loads on Vehicle Barrier Systems.*** *Vehicle barrier systems for passenger vehicles shall be designed to resist a single load of 6,000 lb (26.70kN) applied horizontally in any direction to the barrier system, and shall have anchorages or attachments capable of transferring this load to the structure. For design of the system, the load shall be assumed to act at heights between 1 ft 6 in. (460 mm) and 2 ft 3 in. (686 mm) above the floor or ramp surface, selected to produce the maximum load effect. The load shall be applied on an area not to exceed 12 inches by 12 inches (305 mm by 305 mm), and located as to produce the maximum load effects…*

The two underlined clauses (underline added by author) are prescribed in the Code to be used in design of barrier systems. The author asked the ASCE Standards Committee, ASCE 7, for a formal interpretation of the clauses. The questions submitted for the formal interpretation are summarized below:

1) Are the clauses ambiguous?
2) Are the clauses superfluous and can be ignored in design?
3) Does the clause "t*o produce the maximum load effects*" mean that the single load of 6,000 lb distributed over an area of 12 inches by 12 inches (305 mm by 305 mm) shall produce the maximum shear force, the maximum bending moment and the maximum deflection in the 12-inch wide strip of wall directly under the area, such as shown in *Figure 1*?
4) Does the phrase "*to produce the maximum load effects*" mean that the single load of 6,000-lb shall be distributed over an area not to exceed 12 inches by 12 inches (305 mm by 305 mm) and then spread down to the wall base at the maximum slope reducing the wall bending moment on per unit length basis, such as shown in *Figure 2*?

The ASCE Standards Committee responded that the language in the section 4.5.3 was not ambiguous, and would not be clearer if the words "to produce the maximum load effect" were removed. The author concurs with Standards Committee's response. This paper provides a historical perspective of the reinforced concrete barrier wall design and provides design guidelines.

Barrier walls are commonly termed bumper walls. A bumper wall design example was published in the 1970s in the *Handbook of Concrete Engineering* (Editor: Mark Fintel). The design example used a 6-inch thick cantilevered concrete

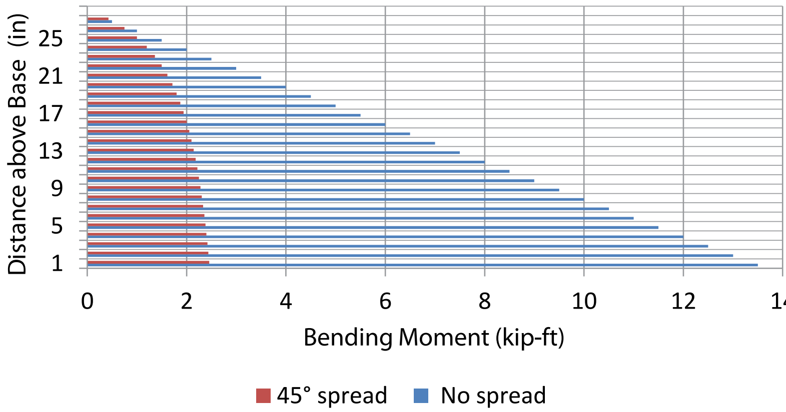

Figure 3. Comparison of wall moments for No-spread and Distribute-and-Spread for a 6-kip load applied 27 inches above wall.

wall reinforced with a single layer (A_{s1}-type) of steel. No other longitudinal, transverse or temperature reinforcement was provided in the example. It was assumed that the point load, *P*, spreads over a 4-foot width of wall. The load spread scheme used in the Handbook is shown in *Figure 2*. It was shown that for a 10,000-lb point ultimate load, which equals a 6,000-lb allowable load, applied at 18 inches above the floor, the wall reinforced with A_{s1} = # 4 @12 inches on center was "OK". No justification for the load spread was given in the Handbook. Though the design example has been commonly followed in the design and construction of bumper walls in concrete parking garages, the underlying 1:1 load spread assumption has not been examined or tested for validity. Assuming any failure pattern or load spread in structural design is generally unsafe and has been termed "half-truth" in the treatise *Yield Analysis of Slabs* (Jones et al., 1967) A proper failure mechanism is one that requires the maximum reinforcement in the bumper wall. This article examines cantilever bumper wall design in light of the ASCE 7-10 language and the principles of structural mechanics. Design guidelines are provided at the conclusion.

"To Produce the Maximum Load Effect"

In engineering terms, the phrase "to produce the maximum load effect(s)" means to produce the maximum shear, torsion, bending moment and deflection in a barrier system under a single point live load. Generally, this point live load needs to be moved and applied at various points within the system to produce the maximum load effects. It is foreseeable that applying the load at any one point may not produce the maximum effects everywhere. For example, the load applied at a wall corner may have one set of "maximum load effects" and the load applied at the wall's free edge may have another. The ASCE 7 standards section 4.5.3 defines the influence surface within which the load should be applied strategically in order to produce the maximum load effects. For bumper walls, this influence area is the full length of the wall in the horizontal direction and from 18 to 27 inches in height above the floor in the vertical direction.

Building codes generally do not prescribe how the single load should be resisted by a barrier wall. There are many ways the wall can be designed for the load to flow from the point of application to the wall base, and then into the structure. The wall segment that participates in resisting the point load depends on the amount and pattern of the wall reinforcement. Consider the code-prescribed load spread provision of "not to exceed 12 inches by 12 inches". Two examples of load-carrying mechanisms concerning the provision are shown in *Figures 1* and *2*. The figures show the part of wall assumed to resist the point load, *P*. In *Figure 1*, a 1-foot wide wall strip is assumed to act as a cantilever. Using the strip mode, the wall requires only A_{s1}-type reinforcement. The temperature reinforcement is required by the code but is excluded from being part of the flexural reinforcement. For the 6-inch concrete wall referenced earlier, subjected to the 10,000-lb point ultimate load at 18 inches above the floor, the steel requirement is about #4@3 inches on center, when considering only a 12-inch wide strip. For the ultimate point load applied at 27 inches above the floor, the steel requirement would increase further for each strip. Such closely-spaced reinforcement may not be desirable or practical and, therefore, an increase in wall thickness and other design options need to be considered. As such, the strip or non-spread method provides a safe, lower bound and conservative design for the bumper wall.

Figure 2 shows the point load, *P*, distributed over a 12-inch (305 mm) length and then assumed to spread downward at 45-degree

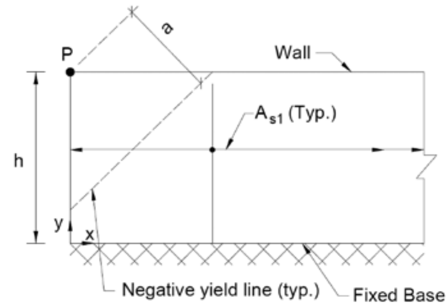

Figure 4. Corner break-off mode with a point load at the corner of the barrier wall.

inclinations on both sides of the load. The spread assumption connotes that a 4-foot length of the wall at the floor level would be engaged in resisting the load. It further implies that the wall design moment reduces to 25% of the no-spread moment. For a barrier load located 27 inches above floor, the wall moment at its base reduces to a mere 18% of the strip mode (*Figure 3, page 13*). This means an 82% reduction in the design moment. The load spread assumption minimizes the design by distributing the load over a larger load. Therefore, the use of the load spread scheme and the associated moment reduction must be justified using structural mechanics and experimental work in order to avoid design deficiency in the wall.

The ACI-318 Approach

The ACI-318 code permits a new structural system or a new design approach if its adequacy has been shown. One way to show this is to successfully test the new system. However, no test data on the 6-inch thick cantilever bumper wall system or the spread assumption could be found. Analytically, the load-carrying mechanism that produces "the maximum load effects" can be determined using the principles of structural mechanics. Both elastic and plastic methods are available for analysis and design of the barrier wall. Finite element analysis is one method and yield-line theory is another method. The ACI Code commentary refers specifically to the yield-line analysis as an acceptable approach.

Yield-line Analysis

A yield-line in a slab (or a bumper wall in this case) corresponds to a plastic hinge in concrete beams. There are two types of yield-lines. A yield-line formed by yielding of positive reinforcement is called a positive yield line. Similarly, a yield-line formed by yielding of negative reinforcement is called a negative yield-line. The moment capacity per unit

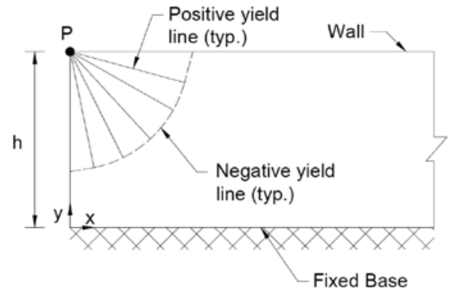

Figure 5. Fan mechanism formation with a point load on the corner of a long wall.

length of the yield-line formed at an angle θ with the x-axis is given by:

$$m_\theta = m_x \cos^2 \theta + m_y \sin^2 \theta \qquad \text{Equation 1}$$

where m_x and m_y are moment capacities of the reinforcement about the x- and y-axis, respectively.

In contrast to the finite element method, which is a computer-based method, the yield-line method requires hand-calculations along with some knowledge of how a bumper wall could fail. The yield-line method is an upper-bound method and provides the bumper wall load-carrying bending capacity when a proper yield-line mechanism is used. For example, consider the cantilever wall shown in *Figure 1* subjected to a single point load, P. In order to design the wall, the load should be moved and applied at various points within the influence surface area in order to produce the maximum load effects. Two load locations significant for design are: the corner and the free edge of the wall.

Point Load at the Corner of the Bumper Wall

Consider a single load, P, applied at the corner of the wall, as shown in *Figure 4*. The simplest failure mode occurs when the wall corner fails as a triangular piece with a negative yield-line at distance, a, from the corner. Consider the 6-inch thick concrete wall reinforced with #4@12 inches on center next to the interior (vehicle side) face of the wall, with the moment capacity of approximately 4ft-kip/ft. Using *Equation 1*,

$m_x = 4$ (ft-k)/ft
$m_y = 0$
$\theta = 45°$
$m_\theta = (4)(\cos^2 45) + (0)(\sin^2 45) = 2$ (kip-ft)/ft
Yield-line length, $l = a + a = 2a$
Moment at the yield-line = $P * a = m_\theta * l$
Therefore, $P * a = (2)\,(2a)$ or $P = 4$ kips < 10 kips

Though the anticipated failure load of 4,000-lb is much less than the design load of 10,000-lb, it is still an upper-bound and unsafe solution. This is because the implicit assumption in this failure mode is that the wall has sufficient positive reinforcement to eliminate formation of positive yield-lines. Because the bumper wall has no positive reinforcement and is only singly-reinforced with A_{s1}-type negative steel, its capacity is expected to be lower than that anticipated by the *Figure 4* mechanism.

If a bumper wall is reinforced with both positive and negative steel, a fan-type mechanism may form which has radial and circumferential yield-lines, as shown in *Figure 5*. The circumferential yield-lines are formed when the negative steel yields and the radial yield-lines are formed when positive steel yields. If the positive steel is omitted altogether, then a quarter-circle of radius, r, could develop with no resistance along the radial lines. Further, the moment capacity A_{s1}-type steel varies along the periphery of the quarter-circle as angle changes. Therefore, the average moment capacity along the circumferential yield-line, m_θ is one-half of the maximum moment the steel can develop. Thus, the failure load, P, can be computed as follows:

Moment at the circumferential yield-line = $P * r = m_\theta\,(2\pi r/4)$

Therefore $P = (2)(\pi/2) = 3.14$ kips < 10 kip

Now, consider an 8-inch thick cantilever bumper wall reinforced with both positive and negative steel in longitudinal and transverse directions, i.e. each way, each face, (A_{s1} thru A_{s4}) with #4@ 12 inches on center. Using a concrete cover of 1.5 inches, the average moment capacity in both the x- and y-directions is approximately 5.2 ft-kip/ft length of the wall. It has been shown that, with positive and negative reinforcements being equal, the fan type mechanism would not materialize and it would be replaced by the single yield-line mechanism (*Figure 4*). Using *Equation 1*,

$m_x = m_y = 5.2$ (ft-k)/ft
$\theta = 45°$
$m_\theta = (5.2)(\cos^2 45) + (5.2)(\sin^2 45) = 5.2$ (kip-ft)/ft
Yield-line length, l = 2a
Moment at the yield-line = $P * a = m\theta * l$
Therefore, $P * a = (5.2)(2a)$ or $P = 10.4$ kips >10 kips

In addition to the failure modes described above, other modes are also possible. The failure mode that predicts the lowest capacity is the most credible upper-bound solution.

Point Load on the Free Edge of a Long Wall

Similarly, for a point load on the free edge of a long wall, both failure modes shown in *Figures 6* and *7* are possible. The mechanisms are similar

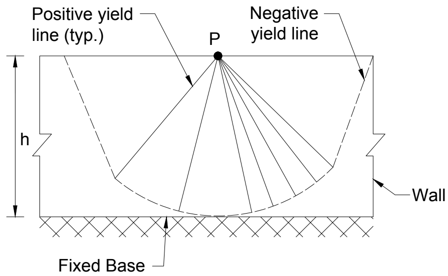

Figure 6. Fan system of yield-lines in wall caused by a point load on the free edge.

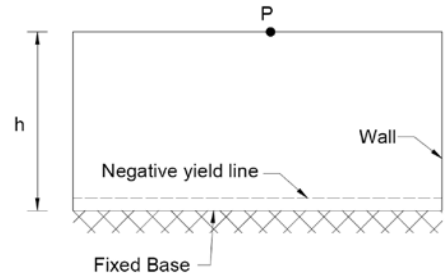

Figure 7. Total collapse mode under a point load applied on the free edge of a wall.

in nature to the mechanisms discussed while addressing the corner load earlier. *Figure 6* shows a general fan mechanism in which the fan and the adjacent yield lines meet. For a wall reinforced with only A_{s1}-type steel, the half-circle long yield negative line could develop with no moment resistance along the radial yield-lines. As noted in the quarter-circle case, the solution is independent of the radius, r, and thus the anticipated failure load is given by:

$P = (2)(\pi) = 6.28$ kips

The mode in *Figure 7* shows the collapse of the entire wall, with the wall-floor joint being the weakest link and developing the yield-line. There are several ways this failure mode can form. One way is to reinforce the wall sufficiently with positive steel to eliminate formation of positive yield-lines. The wall may also collapse as a whole if the wall-slab joint is inefficient. This type of failure mode was also discussed by the author in the April 2014 issue of STRUCTURE magazine. Another reason the entire wall may collapse is the limited extent of the wall length, so that the wall acts as a one strip. Additional failure modes, such as progressive failure or zipper effect, are also possible.

The above examples show how the yield-line method can be used in the analysis and design of the barrier walls. This is generally an upper-bound method, and consequently the true load a wall can resist may be less than the calculated load. This is a recognized concern, since a reasonably prudent design professional prefers to be correct and limit his/her liability by being somewhat conservative. Therefore, the upper-bound solution used in the design of a barrier wall must coincide with the lower-bound solution which gives a conservative or, at most, correct value of the collapse load. Its conditions are:

1) A complete stress field must be found, everywhere satisfying the differential equation of equilibrium.
2) The forces and moments at the edges must satisfy the boundary conditions.
3) At no point can the principal stresses violate the yield criterion.

Simply put, one needs to find the worst (i.e. gravest) layout for the system of yield-lines that produces the smallest load the wall can carry. In corollary, for a prescribed load, one needs to determine the system of yield-lines that produces "the maximum load effects". Thus, every assumption regarding the load-carrying mechanism should be verified using the lower-bound solution.

Summary

It is the customary duty of a design professional to determine the failure pattern which is the most critical and produces "the maximum load effects". The ASCE 7-10 phrase "to produce the maximum load effect" is proper as a design requirement. The yield-line theory provides a satisfactory method in predicting the ultimate load a bumper wall would be able to resist. A proper yield-line or failure mechanism is one that requires the maximum reinforcement in the wall, consistent with analytical and experimental work. While there is a dire need for the code load requirements to be rationally-based, conservative design guidelines for barrier walls using the ASCE 7 code language are:

1) Before assuming any load spread or failure mechanism, verify it experimentally.
2) If no experimental data is available, use the strip mode shown in *Figure 1*.
3) Provide reinforcement each way on each face of the wall, as shown in *Figure 1* and use a minimum bumper wall thickness of 8 inches.
4) Provide a fully efficient wall-floor joint which can transfer the load from the wall to the structure. One way to achieve this is to have the wall supported on a beam, as shown in *Figure 1*.
5) Use the single load application provision "on an area not to exceed 12 inches by 12 inches" for the punching shear check.▪

References

Arthur Nilson, Design of Concrete Structures (1997)

L.L. Jones and R. H. Wood, Yield Analysis of Slabs (1967)

Gerald Kennedy and C. Goodchild, Practical Yield line Design