Chapter 6: Stability

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6-1 Introduction

The term stability, as it is used throughout this manual, means resistance to overturning or collapse of the falsework system or elements of the system under consideration. Resistance to both overturning and collapse is provided by the falsework bracing system, which must be designed to withstand all forces resulting from application of the assumed horizontal load.

The term falsework bracing system as it is used in the specifications includes bracing designed to resist overturning or collapse. Falsework bracing systems are usually comprised of struts, ties, cables, anchor blocks, and similar features used to prevent the overturning or collapse of any falsework component. Regardless of functional elements, the bracing system must be designed to resist all forces generated by the assumed horizontal load.

It is important to recognize the distinction between overturning and collapse, as these terms are used to describe the failure modes when falsework is subjected to horizontal forces. Overturning is used when the bracing provides sufficient rigidity to the system as a whole, or to the element of the system under consideration, so that the system or element acts as a single, rigid unit. In such cases the falsework will fail by overturning, or rotation about its base. If, however, the bracing cannot prevent distortion of the falsework when it is subjected to horizontal forces, the system will collapse internally rather than overturn. The two failure modes are shown schematically in Figure 6-1, *Falsework Failure Modes*.

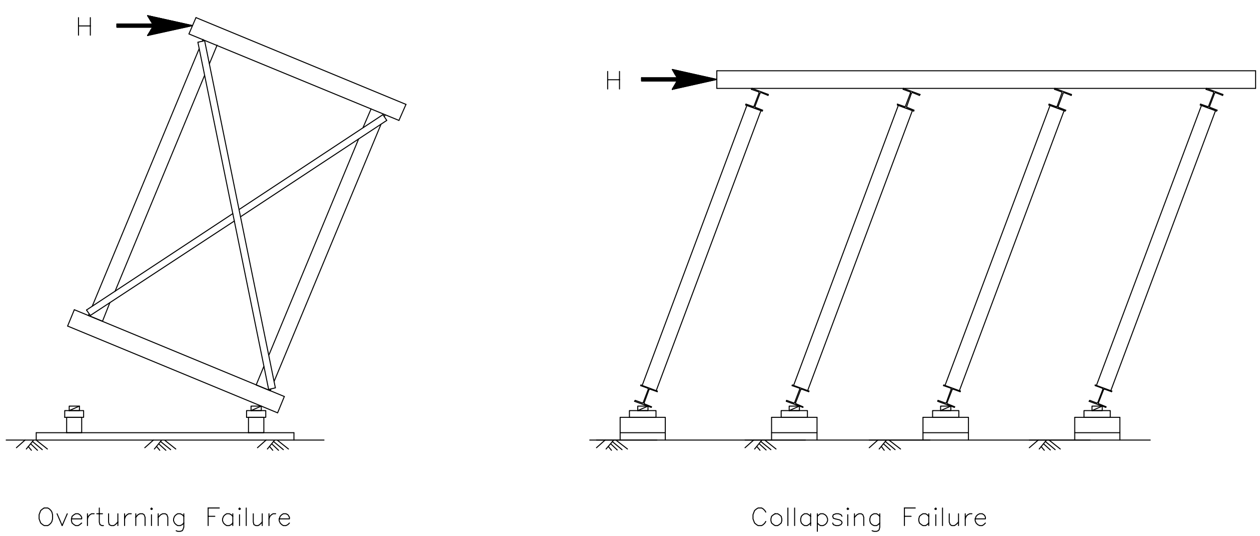


Figure 6-1, Falsework Failure Modes.

The specifications do not require the falsework to carry the assumed horizontal load from its point of application through all members of the system to the ground or other point of support. If the bracing system will resist the overturning and collapsing forces produced by the horizontal design load, then the design complies with the intent of the specifications.

For conventional falsework, experience has shown that the possibility of sliding failure is low. However, sliding failure may occur and engineering judgment should be used when designing and reviewing the falsework. Failure due to sliding is more likely to happen in the unloaded stage of falsework. Sliding must also be considered in each plane between falsework tiers where the posts are discontinuous.

When cables are released for grading or adjustment, pork-chops and come-alongs, or similar systems, must be used to control the release of the cable and to maintain stability of the system. Loosening the clips without control is not acceptable. The system being used to release cables must be shown on the shop drawings.

Stresses in falsework members produced by the application of a horizontal force should be combined with stresses produced by vertical forces to provide stability. This results in additional stresses in an axially loaded member thus decreasing the stability of the system. For additional information see Section 5-7, *Combining Stresses*.

6-2 Inherent Stability

Some falsework systems have inherent stability due to their material properties and geometry used in their construction. For example, timber bents have a degree of inherent resistance to collapse, particularly where short, wide posts are used.

Since the amount of inherent stability developed under a given loading condition is a very intangible factor, the inherent ability of a falsework frame to resist overturning and collapsing forces must be neglected in all cases where:

$$\mathbf{L} > \mathbf{3b} \tag{6-2-1}$$

where **L** = Height of post

b = Width of post

When post height exceeds the limiting ratio, resistance to overturning and/or collapse must be provided by diagonal bracing, blocking, ties, or other means authorized.

6-3 Diagonal Bracing

6-3.01 Introduction

In conventional falsework systems, the individual posts that make up the falsework bent are stabilized against collapse by wood, steel, and cable diagonal cross bracing. The stiffer diagonal braces of wood and steel are installed across two or more vertical posts and securely nailed, bolted, or welded in place to make a single rigid unit capable of resisting the collapsing forces produced by horizontal loads. The more flexible cable bracing is typically installed diagonally from top cap to bottom cap.

6-3.02 Wood Cross Bracing

Studies of the behavior of braced falsework bents have revealed that the actual load imposed on the compression members, under certain loading conditions, may be as much as 2 times greater than would be indicated by a simplified analysis. This is due to the indeterminate nature of braced falsework bents and due to the material properties of wood. To ensure the compatibility of results obtained by our procedure with results obtained by a rigorous frame analysis:

- The contribution of the compression members, and the compression member connections is limited to 1/2 of their theoretical contribution when calculating the resisting capacity of the bracing system

SC has developed a review procedure which simplifies the analysis, and at the same time minimizes the risk of detrimental overstressing of the compression members. This simplified procedure, called the “resisting-capacity” method of analysis, assumes that the collapsing force produced by the assumed horizontal load will be resisted by the sum of the horizontal components of the allowable load carrying capacities of the diagonals. To ensure stability, the sum of the horizontal components (i.e., the resisting capacity of the diagonal braces) must be numerically equal to or larger than the collapsing force.

When compression members have intermediate fasteners to reduce the unsupported length for design, the fasteners must be capable of resisting a force, applied at right angles to the member, equal to:

- 5% of the theoretical design capacity of the member
- Not less than 250 lbs.

When the bracing members are required to be bolted to the main members, other fastener types may be used as intermediate fasteners in the center of a diagonal brace.

To ensure uniformity, the adequacy of diagonal bracing must be checked by the resisting-capacity method. The procedure depends on the number of vertical tiers of bracing used in the bent, as discussed in the following two sections.

6-3.02A Analysis of Single Tier Framed Bents

A single tier framed bent consists of two or more posts braced with one level of diagonal cross bracing.

For single tier bracing, the resisting capacity of the diagonal bracing system is calculated as follows, regardless of the type of fastener (nails, bolts, or lag screws) used in the connection:

1. Determine the strength of the connection between brace and post. The strength value will be the same for both tension and compression members. For this calculation, follow the procedure in Section 5-3, *Timber Fasteners*, for the type of fastener used.
2. Determine the strength of the diagonal braces in tension.
3. Compare the strength value of the connection (from step 1) and the strength of the brace in tension (from step 2). The smaller of these two values is the strength of the tension members.
4. Calculate the horizontal component of the strength value found in step 3. The horizontal component is the resisting capacity of the tension members.
5. Determine the strength of the diagonal braces in compression, as limited by the Column Stability Factor, $\mathbf{C_P}$.
6. Compare the strength of the connection (from step 1) and the strength of the braces in compression (from step 5). The smaller of these two values is the theoretical strength of the compression members. 1/2 of the theoretical strength is the allowable strength of the compression members.
7. Calculate the horizontal component of the allowable strength (step 6) to obtain the resisting capacity of the compression members.
8. Add the resisting capacity of all tension members and all compression members to obtain the total resisting capacity of the diagonal bracing system.

Compare the total resisting capacity of the diagonal bracing system, as determined above, and the assumed horizontal load applied to the falsework bent. The resisting capacity of the bracing system must equal or exceed the horizontal force applied in either direction; otherwise the bracing is not adequate.

The resisting capacity method is illustrated in Example 14, *Diagonal Bracing of Single Tier Framed Bent – Nailed Connections,* and Example 15, *Diagonal Bracing of Single Tier Framed Bent – Bolted Connections,* in Appendix D, *Example Problems*.

6-3.02B Analysis of Multi-Tier Framed Bents

A multi-tiered framed bent consists of two or more continuous posts braced with two or more levels of diagonal cross bracing.

When the diagonal bracing system consists of more than a single tier, the collapsing resistance of the frame may be limited by the resisting capacity of any individual tier of bracing within the frame. The resisting capacity of the bracing in each tier must be evaluated independently of the other tiers to ensure that each independently braced element of the bent (i.e. each tier) can withstand the collapsing force applied to that element.

Excess resisting capacity in one tier may not be used to compensate for a deficiency in the resisting capacity of any other tier.

The resisting-capacity method has been verified by analysis of mathematical models of typical and atypical falsework configurations. These analytical studies reveal that a horizontal brace between the tiers in a multi-tiered frame makes only a marginal contribution to the total resisting strength of the frame, and under some loading conditions may actually decrease (although only slightly) the effectiveness of the compression members as compared to similar frames in which no horizontal braces are used. Since horizontal braces appear to be redundant members of the system, their effect on frame capacity may be neglected when checking diagonal bracing by the resisting-capacity method in all cases where the diagonals are capable of resisting compression.

A horizontal brace will be required between tiers in a multi-tiered frame in those cases where the diagonal braces can carry tension forces only. The reason is that braces in tension will create a lateral load on the post, so a strut is needed to stabilize the post to resist buckling.

6-3.02B(1) Falsework Bent with Equal Height Tiers

When the tiers have equal height, the resisting capacity of each tier is the same given the same bracing and connections. Consider the diagonally braced bent shown in Figure 6-2, *Falsework Bent with Equal Height Tiers*. Evaluating the adequacy of the bracing in a bent where the bracing system is the same in each tier, is simplified by symmetry.

The procedure is as follows:

1. Calculate the resisting capacity of the diagonal bracing in either tier (the values are the same for both tiers). Follow the procedure discussed in Section 6-3.02A, *Analysis of Single Tier Framed Bents*.
2. Compare the total resisting capacity calculated in step 1 and the horizontal force. If the resisting capacity equals or exceeds the horizontal force, the bracing in that tier is adequate, and therefore the bent bracing system is adequate as well.

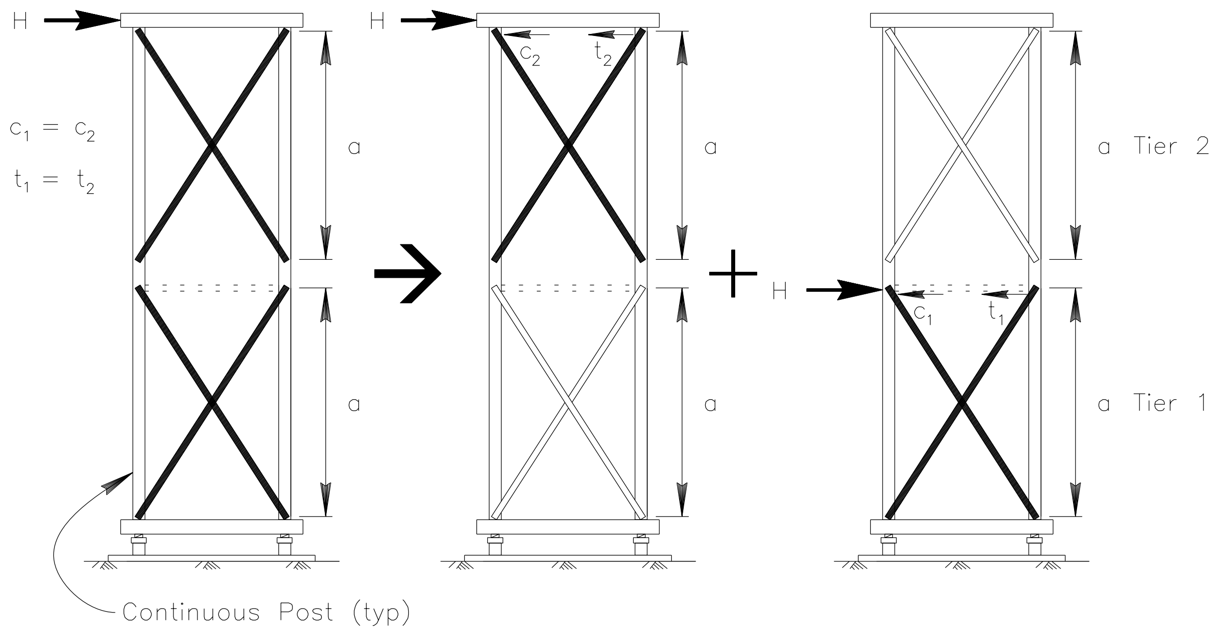


Figure 6-2. Falsework Bent with Equal Height Tiers.

The procedure for evaluating bracing adequacy when the bracing system is the same in each tier, as described herein for a two-tiered bent, will also apply to bents with three, or more, identical tiers of bracing.

6-3.02B(2) Falsework Bent with Unequal Height Tiers

When the tiers are of different heights or are otherwise dissimilar, the resistance provided by the bracing in each tier may not be the same as the resistance provided by bracing in other tiers. Therefore, the resisting capacity of the bracing in each tier must be evaluated independently of the bracing in the other tiers. Consider the diagonally braced bent shown in Figure 6-3, *Falsework Bent with Unequal Height Tiers*.

The procedure is as follows:

1. Calculate the resisting capacity of the bracing in tier 2, following the procedure in Section 6-3.02A, *Analysis of Single Tier Framed Bents.*

2. Compare resisting capacity and horizontal force. For this comparison, the horizontal force is assumed as acting in a plane through the upper connections in the tier 2 bracing. The resisting capacity of the bracing in tier 2 must equal or exceed the collapsing force.
3. Repeat steps 1 and 2 for tier 1.

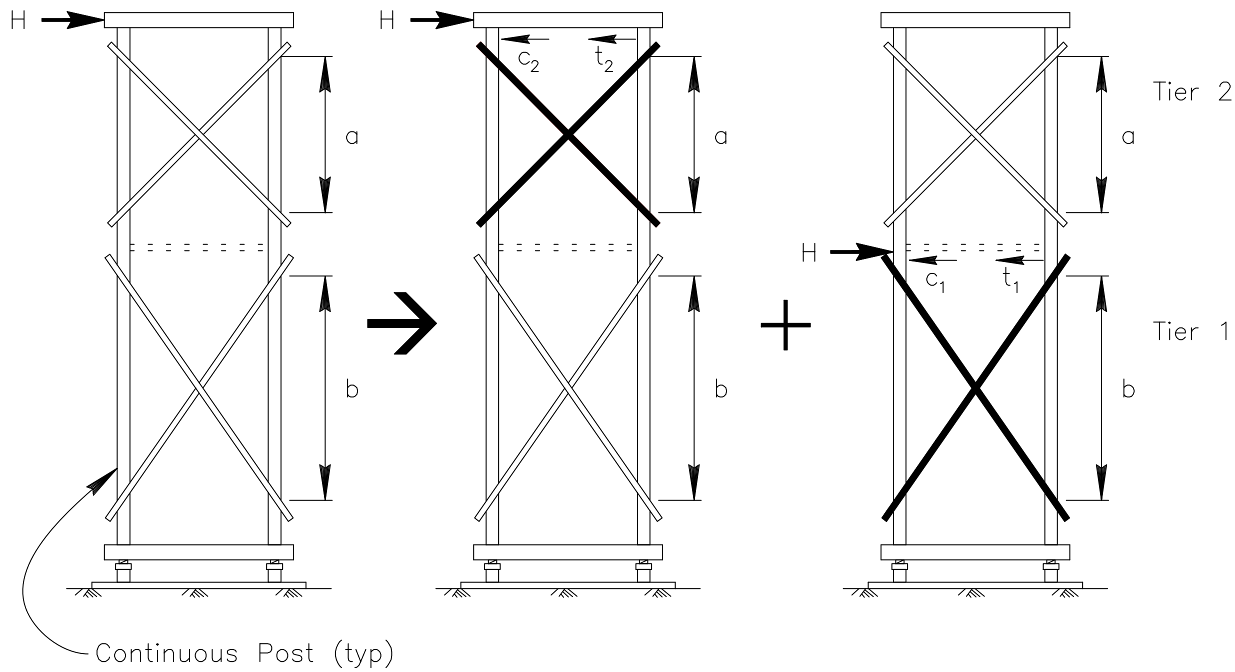


Figure 6-3. Falsework Bent with Unequal Height Tiers.

If the resisting capacity of the diagonal bracing in each tier will withstand the horizontal force applied at that tier, the diagonal bracing system is adequate. If, however, the resisting capacity of either tier is less than the horizontal force, the bracing system is not adequate.

6-3.02B(3) Post Bending

If the tiers of diagonal bracing are closely spaced vertically the effect of bending in the posts between the connections is small and may be neglected when investigating post capacity. If the tiers are separated, however, as shown in Figure 6-4, *Falsework Bent with Separated Tiers,* then bending may be an important factor.

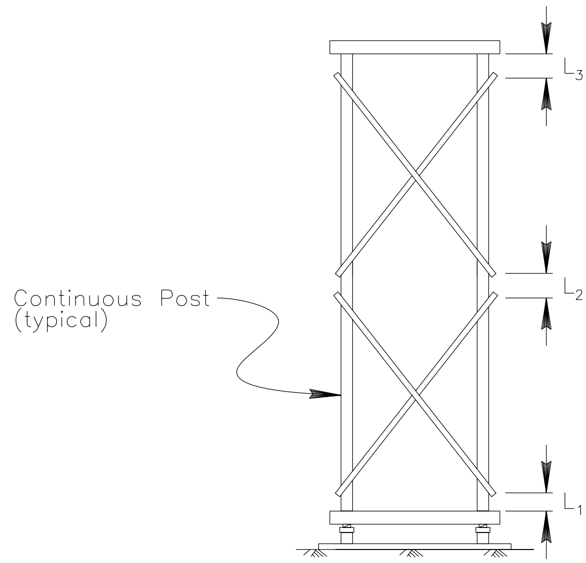


Figure 6-4. Falsework Bent with Separated Tiers.

To ensure uniformity, the effect of bending on post capacity must be investigated if *any* of these conditions are true:

$$\mathbf{L_1 > 4d} \quad (6\text{-}3.02B(3)\text{-}1)$$

$$\mathbf{L_2 > 4d} \quad (6\text{-}3.02B(3)\text{-}2)$$

$$\mathbf{L_3 > 4d} \quad (6\text{-}3.02B(3)\text{-}3)$$

where $\mathbf{L_1}$ = vertical distance below the tiers of bracing

$\mathbf{L_2}$ = vertical distance between the tiers of bracing

$\mathbf{L_3}$ = vertical distance above the tiers of bracing

d = diameter or width of post

When bending in the post is considered, secondary effects due to horizontal deflection (P-Δ effect) must be included. The design must consider the effect of horizontal deflection on member stresses. The analysis for wood posts should follow the procedure for evaluating the adequacy of timber pile bents (see Chapter 8, *Foundations,* except that the posts will be considered as pinned at both the top and bottom.

6-3.03 Steel Bracing

The resisting-capacity method, as discussed in the preceding sections is also applicable when rigid steel bracing (e.g. angle or channel) is used with either steel or timber posts.

Rebar and cable bracing are flexible and are not considered to be rigid bracing. Thus, they do not provide compression resistance in diagonal bracing.

6-3.04 Cable Bracing

For cable bracing see Section 5-5, *Cable Bracing Systems*.

6-4 Longitudinal Stability

6-4.01 Introduction

It is necessary to provide a system of restraint that will prevent the falsework bents from collapsing when the assumed horizontal load is applied in the longitudinal direction. This can be accomplished by diagonal bracing between pairs of adjacent bents, or by transferring the horizontal load from one falsework span to the next falsework span ahead without allowing any horizontal force to reach the bent between the two spans.

6-4.02 Bracing

Consider, for example, the system shown in Figure 6-5, *Braced Falsework System*. Longitudinal forces generated by the assumed horizontal load are carried in either direction across the unbraced bents D and E to the point of longitudinal restraint at bents C and F. The system is stabilized by diagonal bracing between bents B-C and F-G, which are each designed to resist one-half of the total horizontal load acting on the system.

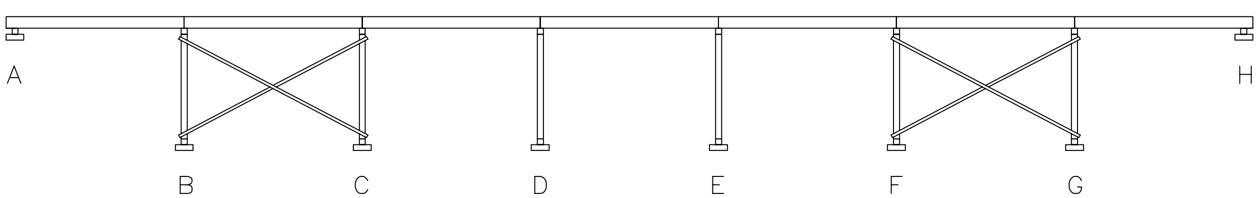


Figure 6-5. Braced Falsework System.

The adequacy of longitudinal bracing used to stabilize adjacent bents will be determined in accordance with the procedure discussed in Section, 6-3, *Diagonal Bracing*.

6-4.03 Friction

The method by which the assumed horizontal load is carried across an unbraced bent should be analyzed to verify that horizontal forces can transfer across the unbraced bent under all loading conditions. Many designs will take advantage of frictional resistance between stringer and cap to transfer at least a part of the total longitudinal force acting at the bent. Friction will not be developed until a vertical load is applied. Therefore, in the unloaded condition do not allow more frictional resistance than will be developed by the dead load of the falsework members plus an allowance for the weight of forms and reinforcing steel.

6-4.04 Devices

If frictional resistance alone is not sufficient to withstand the assumed horizontal load, some positive means of restraint must be provided to carry that portion of the total load in excess of the maximum allowable frictional resistance. Positive means of restraint includes blocking, bracing, dowels, clips, cables, and similar mechanical connecting devices capable of transferring horizontal forces in the absence of a vertical load but does not include C-clamps.

Devices used to transfer horizontal forces across an unbraced bent must be spaced far enough apart transversely to prevent eccentric loading on the restraining member. In general, this will require at least two points of mechanical transfer for each independent element of the system. One-point transfer may be acceptable under unusual circumstances, such as a case where the force to be transferred is small when compared to the total horizontal load, or where each independent element is relatively narrow. This is a matter of engineering judgment. In case of doubt, two points of load transfer should be required.

6-5 Overturning

6-5.01 Introduction

If the falsework system, or the element of the system under consideration, is adequately braced to prevent collapse, the system or element may still fail by overturning, or by rotation about its base, when the assumed horizontal load is applied. Overturning failure will occur unless the falsework is inherently stable against overturning by reason of its configuration or is braced to prevent overturning.

In stability analysis, the assumed horizontal load produces a moment that acts to overturn the system or element of the system under consideration. For descriptive purposes, this moment is called the *overturning* moment.

6-5.02 Overturning of Falsework

When calculating overturning moment, the moment arm will be measured from a plane at the top of the falsework member that is set on the ground, and the assumed horizontal load will be applied to the falsework in accordance with the following:

- Actual loads due to equipment, construction sequence, or other causes, will be considered as acting at the point of application on the falsework.
- Wind loads will be considered as acting at the centroid of the wind impact area for each height zone. When wind loads govern the design, however, the assumed horizontal load, used in calculating the overturning moment, is applied in a plane at the top of the falsework post or shoring. See Section 3-3.03, *Wind Loads*.
- When the minimum load governs the design, it is assumed as acting in a plane at the top of the falsework posts or shoring.

6-5.03 Overturning of Elements or Systems of the Falsework

When calculating the overturning moment acting on other elements or systems of the falsework where stability is a factor for consideration, such as a pony bent system, the moment arm will be measured from the base of that falsework element or system, and the assumed horizontal load will be applied to the falsework in accordance with the following:

- Actual loads due to equipment, construction sequence, or other causes, will be considered as acting at the point of application on the falsework element or system.
- Wind loads will be considered as acting at the centroid of the wind impact area for each height zone. When wind loads govern the design, however, the assumed horizontal load, used in calculating the overturning moment, is applied in a plane at the top of the falsework element or system. See Section 3-3.03, *Wind Loads*.
- When the minimum load governs the design, it is assumed as acting in a plane at the top of the falsework element or system.

6-5.04 Resisting Moments

When a horizontal load is applied to a falsework frame or tower, the overturning moment thus produced will be resisted up to a point by a resisting or righting moment generated by the weight of the total supported dead load. If the resisting moment is greater than the overturning moment, the falsework is stable against overturning and no external bracing will be required. If the resisting moment is less than the overturning moment, the difference must be resisted by bracing, guying cables, or other means of external support.

The resisting moments for falsework:

- In the unloaded condition may include the weight of falsework beams, forms and, reinforcing steel, but not the concrete.
- In the loaded condition may include the weight of falsework beams, forms, reinforcing steel, and the concrete.

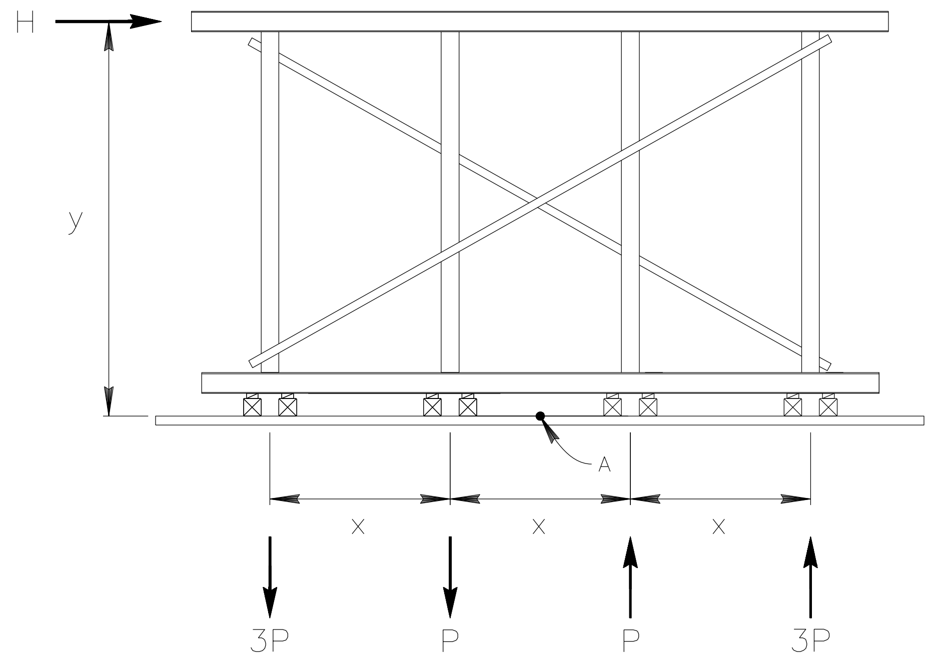
The weight of forms and rebar may be estimated, see Section 3-3.02, *Application*.

6-5.05 Effect of Overturning on Post Loads

When bracing is not required to resist overturning, do not overlook the effect of the overturning moment on post loads when the falsework is fully loaded (including the weight of concrete).

The post load (dead load plus live load) will be increased or decreased by the post reaction created by the overturning moment, or the vertical component of the resisting couple acting through the post. See Appendix D, *Example Problems*, Example 9, *Effect of Overturning on Post Loads.*

In a bent with rigid bracing and more than two posts, the post reactions are proportional to their distances from the center of rotation and may be obtained by algebraic summation, see Figure 6-6, *Effects of Overturning on Post Load*.



$$\Sigma M_A = Hy - [P(0.5x)+3P(1.5x)]2 = 0$$

$$= Hy - 10xP = 0$$

$$P = \frac{Hy}{10x}$$

Figure 6-6. Effects of Overturning on Post Load.

6-6 Tower Stability

6-6.01 Introduction

Falsework towers with discontinuous legs require additional analysis to ensure stability in the various stages of loading. The stages of loading are when the tower is unloaded, when loaded with falsework stringers, and during various loaded conditions involving concrete placement.

6-6.02 Stability

In addition to resisting collapse, the tower must be able to resist overturning and sliding at each plane that the tower is discontinuous.

Loaded towers will generally be capable of resisting overturning moments. However, unloaded towers, both during erection and during removal sequences, are vulnerable to overturning. Removal of portions of tower units while other portions are still loaded can lead to very unstable conditions. It is important to consider the effects of concrete pour sequences and the effects of the concrete weight in a span on one side of the tower and not the other.

Overturning stability of a tower is illustrated in Appendix D, *Example Problems,* Example 7, *Stability of Shoring Towers*.

6-7 Pony Bent Systems

6-7.01 Introduction

Referring to Figure 6-7, *Pony Bent,* a bent stacked on top of another bent is typically called a pony bent. Pony bents are usually erected on, and supported by, a platform constructed at the top of the primary load carrying members. The platform functions as a horizontal diaphragm, and thus stabilizes the entire system. In this system, vertical load continuity and rotation of pony bent due to deflection of lower platform stringer must be accounted for in the design.

6-7.02 Stability

The stability of pony bent systems should be given special consideration. Pony bents should be independently braced, and the bracing must be capable of resisting the overturning moment produced by the assumed horizontal load acting at the top of the pony bent in both the transverse and longitudinal direction. Pony bents are often most vulnerable to overturning during erection and removal. Removal of portions of a pony bent while other portions are still loaded can lead to instability. There have been instances where falsework, which remained in place for an extended period of time collapsed, because the completed bridge deflected and redistributed loads to portions of the falsework.

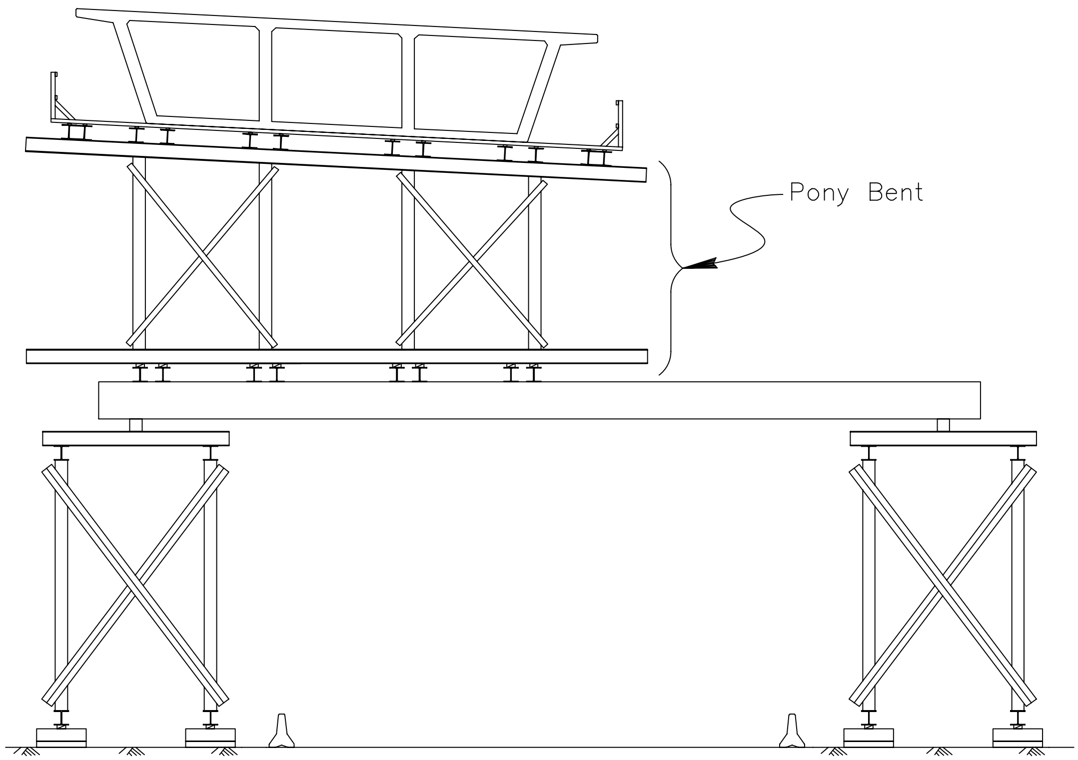


Figure 6-7 Pony Bent.

If a stabilizing platform is not incorporated into the falsework design, the individual bents must be braced or tied together in some manner to prevent lateral displacement at the bottom of the pony bent system.

6-8 Cap Systems

6-8.01 Introduction

In this section the term *cap* refers to top caps and bottom caps. Moreover, Figure 6-8, *Single Bottom Cap,* illustrates bottom caps, however, the requirements for top caps are similar.

The stability of the system will decrease as the distance between the supporting members and the top of the cap increases.

Single cap systems must adhere to the following:

- Maximum height to width ratio of 2:1 in any direction.
- Figure 6-8, *Single Bottom Cap*, shows the criterion for a bottom cap and prevention of overturning perpendicular to the centerline of the cap.

Stacked cap systems must also adhere to the following:

- Maximum height to width ratio of 2:1 in any direction.
- Stacked cap systems must be carefully designed and reviewed to verify stability.

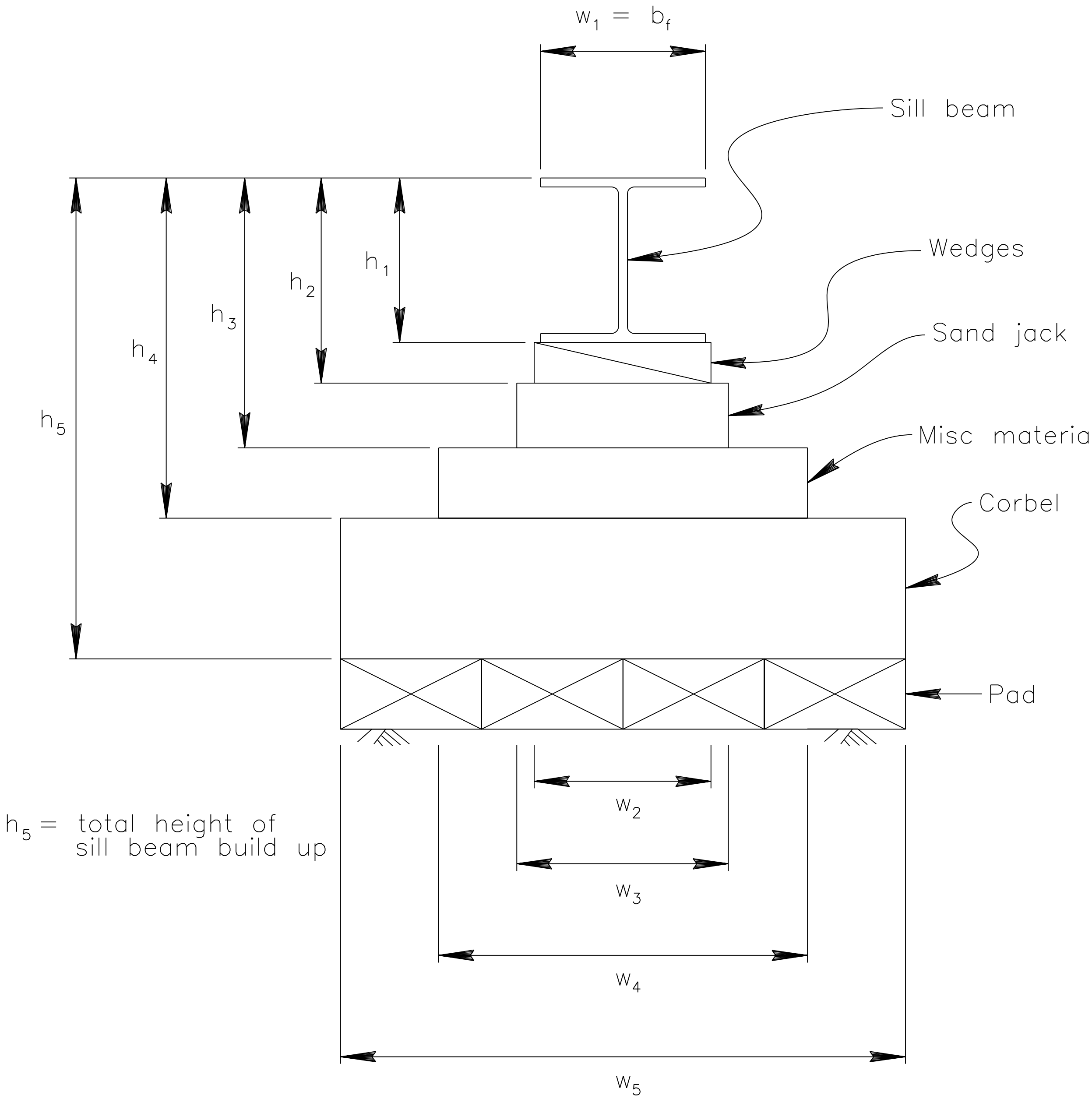
Multiple layers of supporting material must also adhere to a maximum height to width ratio, see Section 6-9, *Build-Up Material*.

The 2:1 height to width criteria must be strictly adhered to during both shop drawing review and construction. Using multiple caps or excessive stacking of material to correct grade errors discovered during falsework construction is an unacceptable construction practice and must not be allowed.

6-8.02 Analysis

The following must be considered when checking the shop drawings:

- All material above the pads or member set on the ground is included when checking the height to width ratio.
- Material size and thickness must be shown on the shop drawings.
- Material must have full bearing and be stacked tight and neat to provide uniform bearing for the supported members.
- Material placed on the sand jack plunger must have full bearing on the plywood plunger and must be clear of the frame of the sand jack by a minimum of 1/4-inch.
- If build-up material is used in the cap system, see Section 6-9, *Build-Up Material,* for the height to width criteria.



To comply with 2:1 depth ratio, $h_i \leq 2w_i$ $(w_i > w_{(i-1)})$

(Overturning perpendicular to bent centerline)

Figure 6-8. Single Bottom Cap.

6-9 Build-Up Material

6-9.01 Introduction

The stability of build-up material decreases as the height of the stack increases. Build-up material must adhere to a maximum height to width ratio of 2:1 in all directions.

The 2:1 height to width criteria must be strictly adhered to during both shop drawing review and construction. Excessive stacking of material to correct grade errors discovered during falsework construction or to accommodate short posts is an unacceptable construction practice and is not allowed.

6-9.02 Analysis

The following must be considered when checking the shop drawings:

- All material above the pads or member set on the ground is included when checking the height to width ratio.
- Material size and thickness must be shown on the shop drawings.
- Material must have full bearing and be stacked tight and neat to provide uniform bearing for the supported members.
- Material placed on the sand jack plunger must have full bearing on the plywood plunger and must be clear of the frame of the sand jack by a minimum of 1/4-inch.
- If caps or stringers are supported by the build-up material, see Section 6-8, *Cap Systems,* for the height to width criteria.