**Technical Note 31A**

**Brick Masonry Arches**

**Draft 2 – 10/07/11**

**Abstract:** Brick arches have been used for over three thousand years. The vast majority of those arches are structural, taking vertical loads above and transferring them to abutments while the bricks of the arch experience mainly compressive forces. This *Technical Note* presents methods for designing various arch types using the principles of engineering mechanics. Using these methods, tables for common arch arrangements are presented. Finally, illustrative examples are included to assist with practical applications of the designs.

**Key Words:** arch, arching action,brick, design, loads, thrust

**SUMMARY OF RECOMMENDATIONS:**

* Determine masonry strength from applicable building codes assuming stack bond within the arch.
* Determine applicable loads, depending on arch type being designed, based on point of application of the loads; arching action diverts some loads to the sides of the arch without putting stress on the arch.
* Determine whether applicable triangular and point loads can be modeled as equivalent uniform loads.
* For shorter spans, lower-rise segmental arches and jack arches, use line of thrust methods for arch design verifying resistance to sliding at the abutment and compressive stress in the arch.
* For longer spans, higher-rise segmental arches and semicircular arches, use elastic deformation theory for design, verifying shear and compressive stresses within the arch and at abutments.
* For asymmetrically loaded arches, which are beyond the scope of this *Technical Note*, use finite element or other analysis methods.
* For all arch designs verify sufficient abutment width to resist horizontal thrust developed within the arch.

**INTRODUCTION**

The gothic cathedrals of Europe are perhaps the most recognizable display of the function of a well-built arch. Vertical loads above the arch are transferred into the arch and slowly rotated by the geometry such that at the base, the loads are held up by walls below and the arch bottom is held inward by buttresses. The units comprising the arch are nearly always in compression with heavy keystones maintaining load on the arch, even before construction above.

Brick arches in use today apply similar principles, though their use is typically limited to two-dimensional wall openings rather than three-dimensional spaces. The wall and other loads above the arch push downward, placing the units of the arch itself in compression. At the base of the arch, the walls below hold the arch and loads up while the abutments resist the outward thrust developed within the arch.

In lightly loaded applications, such as window openings in a veneer, typical construction includes the use of steel lintels to provide support of the masonry above. However, as spans increase and heavier loads are applied, the use of steel introduces significant deflection above the opening which must be accounted for in the design. Brick masonry arches can more easily provide the structural support needed with far less deflection, limiting the potential for damage above or below.

This *Technical Note* is intended to provide sufficient information to design new arches for various applications. For each arch type and design method presented, there are a number of assumptions or limitations that must be followed in order to use the method. These requirements are generally conservative and in line with standard design practices. However, for applications outside the limits presented herein, other methods of design, such as finite element analysis, would have to be performed.

**Nomenclature**

*Technical Note* 31 presents the basic introduction to arch types and components, including defining terminology typically used in arch design. In addition to those items, the calculations and procedures of this *Technical Note* will require the use of a number of variables and properties. They are as defined below and partially depicted in Figure 1. Values with an x subscript refer to properties at any point, x, along the length of the arch.

d – arch depth, in. (m)

Fm – allowable compressive stress, psi (MPa)

Ft – allowable tensile stress due to bending, psi (MPa)

Fv – allowable shear stress, psi (MPa)

f – rise of arch, in. (m)

fm – calculated compressive/tensile stress, psi (MPa)

f’m – specified compressive strength of masonry, psi (MPa)

fv – calculated shear stress, psi (MPa)

H – crown thrust, lb (N)

Hx – horizontal load (thrust), lb (N)

H1 – resisting thrust, lb (N)

HDL – thrust developed from dead load only, lb (N)

k – skewback distance, in. (m)

L – span of arch, in (m)

M, Mx – moment, lb-in (N-m)

Mp – moment due to applied loading between skewback and any point P, lb-in (N-m)

Nx – axial force, lb (N)

n – number of resisting shear planes at abutment

P – applied concentrated load at mid span, lb (N)

Qx – shear force, lb (N)

R – radius of arch (at intrados), in. (m)

t – thickness of arch, in. (m)

V, Vx – vertical force, lb (N)

w – total uniform load, lb/in (N/m)

W – total load from uniform loading, lb (N)

xH – minimum required horizontal dimension of abutment, in. (m)

y0 – location of elastic centroid, in. (m)

Θx – slope of arch, degrees

Φ – angle of skewback with horizontal, degrees

ρ - density of masonry, psf/in. thickness (N/m2/m)



**Figure 1**

**Arch Design Nomenclature**

**Masonry Strength**

The strength of brick masonry is a function of the brick used, the mortar used, and the geometry of the brick/mortar interface (bedding, bond pattern, etc.). For arch construction, the variations are somewhat simplified as the arch can be considered a stack bond element with the head joints, if any, making no contribution to the strength. Further, it is typically unnecessary to grout arch masonry, so strengths based on grouted masonry can be removed. Based on these simplifications, strengths used for arch design can be taken from the MSJC Code, as summarized below. [1]

**Table 1**

**Masonry Strengths for Arch Design**

|  |
| --- |
| *Compressive Strength, psi (MPa)* |
| Brick Strength with Mortar Type | Masonry Strength |
| M, S | N | f’m | Fm |
| 1700 (11.7) | 2100 (14.5) | 1000 (6.89) | 450 (2.76) |
| 3350 (23.1) | 4150 (28.6) | 1500 (10.3) | 675 (4.14) |
| 4950 (34.1) | 6200 (42.7) | 2000 (13.8) | 900 (5.52) |
| 6600 (45.5) | 8250 (56.9) | 2500 (17.2) | 1125 (6.89) |
| 8250 (56.9) | 10,300 (71.0) | 3000 (20.7) | 1350 (8.27) |
| 9900 (68.3) | N/A | 3500 (24.1) | 1575 (9.65) |
| 13,200 (91.0) | N/A | 4000 (27.6) | 1800 (11.0) |
| *Tensile Strength in Bending, psi (MPa)* |
|  | Solid Brick with Mortar Type | Hollow Brick with Mortar Type |
|  | M, S | N | M, S | N |
| PCL (no entrainment) and Mortar Cement Mortars | 53 (0.37) | 40 (0.28) | 33 (0.23) | 25 (0.17) |
| Air-Entrained PCL and Masonry Cement Mortars | 32 (0.22) | 20 (0.14) | 20 (0.14) | 12 (0.08) |
| *Shear Strength, psi (MPa)* |
| Within arch, assuming stack bond | 20 (0.14) |
| Within abutment, assuming running bond | 1.5  |

**Loads**

Loads superimposed on an arch generally fall into three categories. First is the dead weight of masonry above the arch. Second are any applied uniform loads above the arch, such as floors or roofs on loadbearing walls. Third are point loads, such as a beam pocket or exterior appurtenances mounted above the arch. Depending on location and height above the arch, these loads may or may not have to be considered during design.

Due mainly to its typical running bond pattern, brickwork can experience an arching action of loads above an opening. As an illustrative example, consider a new window opening being cut into an existing brick wall, as shown in Figure 2. The brick immediately above the opening have no support below and remain in place only if there is sufficient tensile bond to the brick above. Further above the window, brick can be at least partially supported by brick which overlap the edges of the new opening. The further up one goes, the more support can be offered. As a design condition, arching action can be assumed to handle any loads outside a triangle formed by drawing 45 degree lines up from the corners of an opening.



**Figure 2**

**Arching Action**

The same is true above arched openings. The arch itself only needs to support loads from within the described triangle above the opening, provided there is sufficient uninterrupted masonry above the opening to provide arching action. Therefore the weight of masonry above supported by the arch can be assumed to be the weight of a triangle whose base is the span, L, and height is half the span. For simplicity, this dead load can be simulated using a uniform load over the entire span equalling 2/3 of the peak intensity of the triangular load. Applied loads above the arch are typically only considered if they are within the area of influence above the arch. For high-rise segmental and semicircular arches, where the bottom of the arch is not the same as the base of the assumed triangle, locations of applicable loads are shown in later sections.

For arches where the masonry above the opening is not sufficiently tall to provide arching action, all loads and weight directly above the arch, extending to the top of the masonry, should be considered.

**Thrust Resistance**

The horizontal thrust produced by an arch must be resisted by adjacent masonry elements, typically a wall section. The masonry of the abutment attempts to resist movement, thus exerting a resisting thrust, along lines AD and BC of Figure 3. Where masonry is not sufficiently tall above the base of the arch, the upper line of resistance cannot be fully developed and only one surface can resist the thrust.



**Figure 3**

**Thrust Resistance at Abutments**

Lines AD and BC typically follow an angle roughly lining up with the stair step of the joints in running bond. However, the exact path of the highest stresses (where cracks would first occur) can be difficult to predict with precision. Instead, only the horizontal components of the thrust resistance are considered, as if the line of resistance were horizontal, lining up with points D and C. Thus, the resisting force is the available shear stress that could develop along lines DE and CF (or along line CF only if the masonry of the abutment is insufficiently tall):

 H1 = FvnxHt Eq. 1

To determine the needed abutment width from the end of the arch axis to an opening or corner, H1 is set to the developed thrust, H and equation 1 solved for xH:

 xH = Eq. 2
Note that the selection of n should be made with caution. The development of thrust resistance will depend on the adjacent building geometry. In most cases, the shortest distance to a free surface lies along a single line, either horizontal or diagonal, and n should be set to 1, signifying a single line of thrust resistance.

In addition, the effects of the arch thrust on the overall stability of the abutment must be considered. Typically, there is a risk of rotation or overturning of the abutment only where the arch thrust is near the top of a wall panel or column of masonry.
**DESIGN PROCEDURES**

An arch is essentially a beam curved in the plane of the loads. Any section in the arch, therefore, may be subjected to moment and shear, as in an ordinary beam. In addition, it is subjected to thrust along its axis from components of vertical loads.

In a fixed arch, as all masonry arches are, three conditions must be maintained to insure pure arch action:

1. Length of span must remain constant
2. Elevation of the ends must remain unchanged
3. The inclination of the skewback must be fixed.

If any of these conditions are violated by sliding, settlement, or rotation of the abutments, critical stresses, for which the arch was not designed, can develop. Such stress can result in failure of the arch.

Theories for the design of masonry arches are methods of verification. Dimensions of the arch are first assumed, based on common practice or an empirical formula, and the assumed arch is tested by one or more of the theories.

There are two classes of theories of the stability of a masonry arch: the line of thrust theories and the elastic deformation theories. The line of thrust theories consider the stability of the arch based on a combination of friction and the reaction between the several arch sections. The elastic theories consider the arch as a curved beam whose stability depends upon internal stresses.

In general, the line of thrust theories are most applicable to symmetrical masonry arches loaded uniformly over the entire span or subjected to symmetrically placed concentrated loads. For such arches, the line of resistance, which is the line connecting the points of application of the resultant forces transmitted to each voussoir, is required to fall within the middle third of the arch section so that neither the intrados nor extrados of the arch will be in tension. Essentially the theories ignore the tensile strength of the bond of mortar to brick and rely on friction and compression to keep the arch in place.

For arches which may develop tensile stresses in the arch, such as those subjected to non-symmetrical loading, the elastic theories provide a more accurate method of analysis than the line of thrust theories.

This *Technical Note* will present line of thrust methods for minor segmental and jack arches and an elastic deformation theory for major segmental and semicircular arches. For other design geometries, or for arch designs that do not fall within the set of assumptions presented in each section below, a more stringent analysis, outside the scope of this *Technical Note*, would be required. Most such analyses are currently being performed using finite element modeling.

**Segmental Arches**

A segmental arch, by definition, is a portion of a circle. Therefore, its geometry is easily defined in terms of coordinate systems. In Figure 4, x and y coordinates have their origin at the center point used to trace the arch’s intrados, axis, and extrados. However, x’ and y’, with the origin at the left springing of the arch, are often a more convenient reference.



**Figure 4**

**Segmental Arch Geometry**

**Minor Segmental Arches.** Using a line of thrust analysis to determine compressive stresses and thrust resistance locations in an arch incorporates some inherent assumptions. Specifically, no moments within the arch or at the skewback are considered. This assumption starts to break down with longer spans, higher loads and/or asymmetric loading. Therefore, in order to use line of thrust analysis, the segmental arch must be considered “minor” and adhere to the following limitations:

1. The span of the arch does not exceed 6 ft. (1.83 m)
2. The rise of the arch does not exceed 0.15 times the span (f/L < 0.15)
3. No heavy concentrated loads bear directly on the arch
4. All applied loads are symmetric with respect to the arch.

The first step in designing a minor segmental arch is to determine the appropriate value for the applied uniform load, w. The first component would be the weight of masonry supported. As explained earlier, this weight can be represented by a triangle with 45 degree angles extending up from the sides of the opening. For design purposes, a uniform load of 2/3 the peak intensity of the triangular load can be considered equivalent. The second component of the applied load would be any uniform load (floor, roof, etc.) that is applied within a distance L/2 above the spring line. It is customary to apply this uniform load over the entire length of the arch, even though only a portion may lie within the triangle described above. Finally, the last component of the applied load would be contributions from symmetric concentrated loads. For design purposes, a uniform load whose total load is twice the sum of the concentrated load can be considered equivalent.

In addition to the applied loads, a designer must consider the self-weight of the arch itself, that is, all masonry from the springing to the top of the arch brick at the peak. Though part of this weight bridges directly to abutments, it is recommended to use the entire weight, applied as a uniform load, for design purposes. For the segmental arch, this uniform load due to weight is as computed using Equation 3.

 tρ Eq. 3

Once the total uniform load is known, the next step in the design is to determine the equilibrium polygon, that is, the line of thrust at any point in the arch to maintain stability. Historically, this polygon was drawn on a profile of the arch with intersecting lines representing the points of application of thrust at each voussoir. However, if it is assumed that the arch is segmented into a sufficient number of pieces, as is typically the case for brick masonry arches, the graphical approach can be replaced with a closed-form solution that is more easily placed in a spreadsheet or other analysis program.

To determine the thrust along the arch, half the total arch must be considered. In that half, there are 3 resultant forces: the reaction at the abutment, the applied vertical load, and the horizontal thrust at the crown of the arch (the other half pushing against the half being considered). The crown thrust, equal to the horizontal component of the reaction, is unknown. Therefore, the arch is assumed to be on the edge of instability: the crown thrust is assumed to act at the upper third point, a distance of d/6 above the axis and the reaction is assumed to act at the lower third point, a distance of d/6 below the axis. These locations represent a zero stress condition at the crown of the intrados and springing of the extrados. For equilibrium, setting the sum of the moments about any point to zero determines the value of H:

 Eq. 4

At any point between the abutment and the crown, the thrust can be determined by setting the horizontal component to the crown thrust, H, and the vertical component to the portion of the uniform load seen in the section considered. The slope of the thrust is therefore a function of the change in rise (the run stays constant):

 Eq. 5

The equilibrium polygon can be determined by applying the slope along the length of the arch, as determined at various points along the arch. Assuming infinitesimally small sections, the slope can integrated to find the path of the equilibrium polygon. Therefore:

 Eq. 6

Given the location of the thrust, the arch can be checked for stability against rotation at any point by checking that the thrust acts within the middle third of the arch depth. Given the assumptions used to derive the location of the thrust as being just on the edge of unstable, for a uniformly loaded segmental arch, stability is automatically met. For asymmetric loadings, Equation 6 must be re-derived and, using relationships of coordinates similar to those in Figure 4, the checking equation becomes:

 Eq. 7

Next the arch must be checked for resistance to sliding between voussoirs or at the skewback. Effectively, this is a measure of the amount of shear load at the joints and whether they would overcome friction, without regard to additional strength offered by bond to the mortar. This check is typically performed by comparing the angle at which thrust occurs to the angle of the normal to the voussoir surface (slope of the arch taken at the axis) at any point. For segmental arches where joints are radial, the difference in angles is the greatest at the skewback; therefore, this is the location where the most shear is developed.

The friction coefficient for masonry can be taken as 0.45, corresponding to a friction angle of approximately 24 degrees. Provided the difference in angles described above is less than 24 degrees, the joint resists sliding and the arch is stable.

The slope of the arch at the skewback can be determined by:

  Eq. 8

Using Equation 5 to determine the slope of the thrust, the checking equation for stability against sliding becomes:

 Eq. 9

Note that for the uniformly loaded segmental arch, the first term of Equation 8 reduces to be independent of the applied load.

Lastly, the arch must be checked for compressive stress. Though the stress can be checked at any point within the arch using the developed thrust, for segmental arches, the maximum thrust and therefore stress, is at the skewback. Transforming the horizontal and vertical components of the reaction at the skewback into normal and shear components, after some trigonometric work:

 Eq. 10

With the normal force acting as the resultant of a triangular stress distribution (zero stress at outer edge), the maximum compressive stress becomes:

 Eq. 11

**Major Segmental Arches.** For arches which do not meet the limitations placed on the use of the line of thrust analysis method presented above, additional analysis must be performed. In these cases, the effects of moments, both at the skewbacks and within the arch itself, are considered. Further, the effects of mortar bond as relates to tensile and shearing strength are included in the analysis. Though this method can be used to verify virtually any segmental arch, it does not include provisions for displacement or deformation of the arch. In large constructions, or where loadings are not symmetric, these movements may become significant to the design. Therefore, the following limitations are recommended for use of this design method:

1. The span of the arch does not exceed 20 ft. (6.1 m)
2. No heavy concentrated loads bear directly on the arch
3. All applied loads are symmetric with respect to the arch.

The first step in the design process is to determine the applied loading. As explained above, arching action occurs to divert loading around an opening, leaving an approximately triangular area exerting force on the lintel or arch. However, as arches rise higher into the assumed triangle, the arching action becomes somewhat more difficult to predict. Therefore, for higher rise segmental arches (f/L > 0.29), the following should be used to decide which loads should be included in the analysis.

1. Weight is assumed to be a uniform load of 2/3 the peak intensity of the trianglar load, as described for minor segmental arches
2. Referring to Figure 5, uniform loads below line 1 and concentrated loads below line 2 are not permitted
3. The sum of uniform loads applied between lines 1 and 3 is applied over the length of the arch
4. The sum of symmetric concentrated loads applied between lines 2 and 4 is applied at the midspan of the arch
5. Concentrated loads applied between lines 4 and 5 can be either applied as item 4 above or can be divided by the span length and applied as part of the uniform load
6. Uniform loads above line 3 and concentrated loads above line 5 can be ignored provided sufficient masonry is present to allow arching action to occur.



**Figure 5**

**Load Locations for High-Rise Segmental Arches**

The next step is to overcome the issue of a fixed arch being statically indeterminate. The approach proposed by Shrive, et al. involves replacing the left support with an infinitely rigid arm that is connected to the left end of the arch and extends to the elastic centroid of the arch [3]. By applying a negative moment and positive horizontal and vertical forces to the arm at the elastic centroid rather than at the springing, the arch can be analyzed in sections, as was done for minor segmental arches.

In the Shrive paper, it was assumed that the material properties and section of the arch could vary along its length, thereby giving a variable stiffness. However, if for purposes of this *Technical Note*, it is assumed the material and section properties of a masonry arch do not vary, the elastic centroid is the same as the centroid of the area of the arch and the applied moments and forces are independent of the stiffness of the arch:

 Eq. 12

 Eq. 13

 Eq. 14

 Eq. 15

 where ds is the incremental distance along the arch and x and y are centered at the elastic centroid.

The integrals given in Equations 12 through 15 can be solved directly using commercially available software, but solving manually becomes cumbersome due to the relationship between the arch length, s, and the x,y coordinate system. It is typically easier to input the arch geometry into a spreadsheet, breaking the arch into a sufficient number of segments to give accurate results. For each segment, dx is typically constant, dy and ds are a function of the arch geometry, and Mp is a summation of all moments up to the centroid of the section in question (P only applies to sections extending into the right half of the arch):

 Eq. 16

With the values of M, V, and H known (V being half the total applied vertical load), the internal loadings of the arch can be determined by considering a section of the arch as shown in Figure 6. Because of the symmetry of loading, only one half of the arch need be considered.



**Figure 6**

**Arch Section Equilibrium Analysis**

By summing forces and moments about the point, p, we find that for any point along the left half of the arch:

 Eq. 17

 Eq. 18

 Eq. 19

Once the loads are calculated, the stress state of the arch can be determined. The normal and shear loads are calculated using variations of Equation 10:

 Eq. 20

 Eq. 21

The stresses at the extrados and intrados are determined using a stress distribution block similar to one of those pictured in Figure 7 (note the direction change in Nx).



**Figure 7**

**Stress Distribution in Unreinforced Masonry**

 Eq. 22

 Eq. 23

At each increment of x, values for the compressive stress and tensile stress (if any) should be checked against Fm and Ft. For shear, where the stress exceeds Fv, corresponding to the case where the joint cracks,it should be verified that there is sufficient friction to accommodate the excess load and avoid displacement of elements of the arch.

**Semicircular and Horseshoe Arches**

In studying the stress distributions of high-rise segmental arches, it is seen that the tensile stresses along the extrados are maximum at a point approximately 0.5R up from the center point of the arch. Below that point, the arch masonry acts essentially as part of the abutment. Therefore, semicircular arches can be designed as segmental arches with a springing at y = 0.5R as shown in Figure 8. This changes the point at which the abutment needs to be measured, requiring slightly less abutment width to be built. Horseshoe arches can similarly be reduced, for design purposes, to the same segmental arch; the contribution of the extra masonry at the base of a horseshoe arch is ignored.



**Figure 8**

**Semicircular as Equivalent Segmental Arch**

From the geometry in Figure 8, the parameters for the equivalent segmental arch are:

 Eq. 24

 Eq. 25

**Jack Arches**

Jack arch design is simpler than that for segmental arches, as the geometry of the arch is based on a linear, rather than curvilinear, relationship. Further, the jack arch has been refined over the years to nearly a single set of geometric proportions. For jack arch design, the following geometry, as shown in Figure 9, should be used:

* The skewback distance is ½ in. (12.7 mm) per foot (305 mm) of span for each 4 in. (102 mm) of arch depth.
* The jack arch should have a camber of 1/8 in. (3.2 mm) per foot (305 mm) of span.



**Figure 9**

**Jack Arch Geometry**

As with minor segmental arches, in order to use line of thrust analysis, certain limitations on the jack arch apply:

1. The span of the arch does not exceed 10 ft. (1.83 m)
2. No heavy concentrated loads bear directly on the arch
3. All applied loads are symmetric with respect to the arch.

Within these assumptions, the design of the jack arch follows closely with that of a minor segmental arch, as explained above. First, loading of the arch is determined using uniform and point loads applied in the right triangle above the opening with a height of L/2 at midspan. Given these loads and the assumption that the crown thrust acts at a distance 2d/3 from the spring line and the reaction at the abutment acts at d/3 up from the spring line, summing moments at the abutment gives:

 Eq. 26

 Eq. 27

With H and V known, the arch can first be checked for sliding at the abutment, making sure the angle of the reaction at the skewback does not exceed the friction provided:

 Eq. 28

Lastly, the jack arch must be checked for crushing of the brick. For short span and lightly loaded arches, the point of maximum compressive force is at the skewback. For long span jack arches, the maximum compressive stress is at the midspan. Therefore, both locations should be checked. Using the relationships established in Figure 9 and Equations 26 and 27 and transforming to loads normal to the surfaces:

 Eq. 29

 Eq. 30

**Parabolic Arches**

A parabolic arch is a curvilinear arch whose axis follows the shape of a parabola rather than a circle, as seen, for example, in the Gateway Arch in St. Louis, Missouri. The advantage of a parabolic arch is that it transfers vertical loads to compressive loads in the arch more efficiently than does a semicircular or segmental arch. For this reason, these arches have been used throughout history to carry bridges and other large loads using materials, such as masonry or stone, whose strength lies in compression rather than tension. The disadvantage of the arch is its more complex geometry. This translates to a more difficult fabrication of centering or shoring and potentially a more costly installation.

The design of masonry parabolic arches is beyond the scope of this *Technical Note*. Should the analysis of an existing arch or design of a new parabolic arch be needed, the reader is referred to Section 22 of Frames and Arches, by Valerian Leontovich. [2]

**DESIGN TABLES**

Using the procedures above and typical masonry strengths the following tables were developed as design guides. All the assumptions and limitations given in sections above apply to the use of these tables. Table 2 reports loads using the methods described for minor segmental arches above. However, for some arch geometries, the methods for major arches may permit higher loads.

**Table 2**

**Maximum Equivalent Applied Uniform Load – Minor Segmental Arches, lb/ft per inch of Arch Thickness (N/m per mm)1,2**

|  |  |
| --- | --- |
| Arch Span, in. (mm) | Arch Depth, in. (mm) |
| 4 (102) | 8 (203) |
| f/L = 0.05 | f/L = 0.10 | f/L = 0.15 | f/L = 0.05 | f/L = 0.10 | f/L = 0.15 |
| f’m = 1200 psi (8.28 MPa)(Min. brick unit strength 3000 psi (20.7 MPa), Type N, S, or M mortar) |
| 24 (610) | 300 (172) | 400 (230) | 480 (276) | 860 (494) | 980 (563) | 1070 (615) |
| 36 (914) | 160 (92) | 240 (138) | 300 (172) | 460 (264) | 580 (333) | 660 (379) |
| 48 (1219) | 110 (63) | 170 (98) | 220 (126) | 300 (172) | 400 (230) | 470 (270) |
| 60 (1524) | 83 (48) | 130 (75) | 170 (98) | 210 (121) | 300 (172) | 370 (213) |
| 72 (1829) | 65 (37) | 100 (57) | 140 (80) | 160 (92) | 240 (138) | 300 (172) |
|  | f’m = 2000 psi (13.8 MPa)(Min. brick unit strength 6200 psi (42.7 MPa), Type N mortar, orMin. brick unit strength 4950 psi (34.1 MPa), Type S or M mortar) |
| 24 (610) | 500 (287) | 670 (385) | 800 (460) | 1440 (827) | 1640 (942) | 1790 (1028) |
| 36 (914) | 280 (161) | 410 (236) | 510 (293) | 770 (442) | 970 (557) | 1110 (638) |
| 48 (1219) | 190 (109) | 290 (167) | 370 (213) | 500 (287) | 670 (385) | 800 (460) |
| 60 (1524) | 140 (80) | 220 (126) | 290 (167) | 360 (207) | 510 (293) | 620 (356) |
| 72 (1829) | 110 (63) | 180 (103) | 230 (132) | 280 (161) | 400 (230) | 500 (287) |
|  | f’m = 3000 psi (20.7 MPa)(Min. brick unit strength 10,300 psi (71.0 MPa), Type N mortar, orMin. brick unit strength 8250 psi (56.9 MPa), Type S or M mortar) |
| 24 (610) | 760 (437) | 1020 (586) | 1210 (695) | 2170 (1247) | 2460 (1413) | 2690 (1546) |
| 36 (914) | 430 (247) | 620 (356) | 770 (442) | 1170 (672) | 1460 (839) | 1680 (965) |
| 48 (1219) | 290 (167) | 440 (253) | 560 (322) | 760 (437) | 1010 (580) | 1200 (689) |
| 60 (1524) | 210 (121) | 340 (195) | 430 (247) | 550 (316) | 770 (442) | 930 (534) |
| 72 (1829) | 170 (98) | 270 (155) | 360 (207) | 420 (241) | 610 (350) | 760 (437) |
|  | f’m = 4000 psi (27.6 MPa)(Min. brick unit strength 11,500 psi (79.3 MPa), Type S or M mortar) |
| 24 (610) | 1020 (586) | 1360 (781) | 1620 (931) | 2900 (1666) | 3290 (1890) | 3590 (2063) |
| 36 (914) | 570 (328) | 830 (477) | 1020 (586) | 1560 (896) | 1950 (1120) | 2240 (1287) |
| 48 (1219) | 380 (218) | 590 (339) | 750 (431) | 1010 (580) | 1350 (776) | 1610 (925) |
| 60 (1524) | 280 (161) | 450 (259) | 580 (333) | 730 (419) | 1030 (592) | 1250 (718) |
| 72 (1829) | 220 (126) | 370 (213) | 480 (276) | 570 (328) | 820 (471) | 1020 (586) |
| 1Values are in addition to self-weight, assumed to be 10psf/in. thickness (18.9 N/m2 /mm thickness)2Interpolation is permitted. |

**Table 3**

**Maximum Equivalent Applied Uniform Load – Major Segmental Arches, lb/ft per inch of Arch Thickness (N/m per mm), Applied P = 0 lb (0 N)1,2**

|  |  |
| --- | --- |
| Arch Span, ft (m) | f’m = 1200 psi (8.28 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 3000 psi (20.7 MPa), Type N, S, or M mortar) |
| f/L = 0.05 | f/L = 0.10 | f/L = 0.15 | f/L = 0.20 | f/L = 0.25 | f/L = 0.303 |
| Arch Depth = 8 in. (203 mm) |
| 2 (0.61) | 580 (333) | 1030 (592) | 1360 (781) | 1570 (902) | 1700 (977) | 1780 (1023) |
| 4 (1.2) | 290 (167) | 530 (305) | 690 (396) | 780 (448) | 820 (471) | 820 (471) |
| 6 (1.8) | 195 (112) | 350 (201) | 450 (259) | 490 (282) | 490 (282) | 470 (270) |
| 8 (2.4) | 145 (83) | 260 (149) | 320 (184) | 340 (195) | 330 (190) | 300 (172) |
| 10 (3.0) | 114 (66) | 200 (115) | 250 (144) | 250 (144) | 230 (132) | 210 (121) |
| 12 (3.7) | 93 (53) | 167 (96) | 199 (114) | 195 (112) | 175 (101) | 44 (25) |
| 14 (4.3) | 78 (45) | 139 (80) | 162 (93) | 154 (88) | 133 (76) | 10 (6) |
| 16 (4.9) | 67 (38) | 118 (68) | 134 (77) | 123 (71) | 39 (22) | NP |
| 18 (5.5) | 58 (33) | 102 (59) | 112 (64) | 100 (57) | 9 (5) | NP |
| 20 (6.1) | 51 (29) | 88 (51) | 95 (55) | 81 (47) | NP4 | NP |
|  | Arch Depth = 12 in. (305 mm) |
| 2 (0.61) | 840 (483) | 1480 (850) | 1930 (1109) | 2230 (1281) | 2430 (1396) | 2560 (1471) |
| 4 (1.2) | 430 (247) | 790 (454) | 1030 (592) | 1190 (684) | 1270 (730) | 1320 (758) |
| 6 (1.8) | 290 (167) | 530 (305) | 690 (396) | 780 (448) | 810 (465) | 820 (471) |
| 8 (2.4) | 210 (121) | 390 (224) | 510 (293) | 560 (322) | 570 (328) | 550 (316) |
| 10 (3.0) | 171 (98) | 310 (178) | 390 (224) | 420 (241) | 420 (241) | 400 (230) |
| 12 (3.7) | 141 (81) | 250 (144) | 320 (184) | 330 (190) | 320 (184) | 300 (172) |
| 14 (4.3) | 119 (68) | 210 (121) | 260 (149) | 270 (155) | 250 (144) | 230 (132) |
| 16 (4.9) | 102 (59) | 186 (107) | 220 (126) | 220 (126) | 200 (115) | 132 (76) |
| 18 (5.5) | 89 (51) | 162 (93) | 192 (110) | 188 (108) | 167 (96) | 36 (21) |
| 20 (6.1) | 78 (45) | 142 (82) | 166 (95) | 158 (91) | 137 (79) | 8 (5) |
|  | f’m = 2000 psi (13.8 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 6200 psi (42.7 MPa), Type N mortar, orMin. brick unit strength 4950 psi (34.1 MPa), Type S or M mortar) |
| f/L = 0.05 | f/L = 0.10 | f/L = 0.15 | f/L = 0.20 | f/L = 0.25 | f/L = 0.30 |
| Arch Depth = 8 in. (203 mm) |
| 2 (0.61) | 970 (557) | 1730 (994) | 2270 (1304) | 2620 (1505) | 2840 (1632) | 2970 (1706) |
| 4 (1.2) | 490 (282) | 900 (517) | 1160 (666) | 1310 (753) | 1370 (787) | 1380 (793) |
| 6 (1.8) | 330 (190) | 590 (339) | 760 (437) | 820 (471) | 830 (477) | 800 (460) |
| 8 (2.4) | 240 (138) | 440 (253) | 550 (316) | 580 (333) | 560 (322) | 520 (299) |
| 10 (3.0) | 196 (113) | 350 (201) | 420 (241) | 430 (247) | 400 (230) | 360 (207) |
| 12 (3.7) | 161 (93) | 280 (161) | 340 (195) | 330 (190) | 300 (172) | 44 (25) |
| 14 (4.3) | 136 (78) | 240 (138) | 270 (155) | 260 (149) | 230 (132) | 10 (6) |
| 16 (4.9) | 118 (68) | 200 (115) | 230 (132) | 210 (121) | 39 (22) | NP |
| 18 (5.5) | 103 (59) | 178 (102) | 198 (114) | 179 (103) | 9 (5) | NP |
| 20 (6.1) | 91 (52) | 157 (90) | 169 (97) | 149 (86) | NP | NP |
|  | Arch Depth = 12 in. (305 mm) |
| 2 (0.61) | 1410 (810) | 2480 (1425) | 3230 (1856) | 3730 (2143) | 4060 (2333) | 4270 (2453) |
| 4 (1.2) | 730 (419) | 1320 (758) | 1730 (994) | 1990 (1143) | 2130 (1224) | 2210 (1270) |
| 6 (1.8) | 490 (282) | 890 (511) | 1160 (666) | 1300 (747) | 1360 (781) | 1370 (787) |
| 8 (2.4) | 360 (207) | 670 (385) | 860 (494) | 940 (540) | 960 (552) | 940 (540) |
| 10 (3.0) | 290 (167) | 530 (305) | 670 (385) | 720 (414) | 710 (408) | 680 (391) |
| 12 (3.7) | 240 (138) | 440 (253) | 540 (310) | 570 (328) | 550 (316) | 510 (293) |
| 14 (4.3) | 200 (115) | 370 (213) | 450 (259) | 460 (264) | 440 (253) | 400 (230) |
| 16 (4.9) | 178 (102) | 320 (184) | 380 (218) | 380 (218) | 350 (201) | 132 (76) |
| 18 (5.5) | 157 (90) | 280 (161) | 330 (190) | 320 (184) | 290 (167) | 36 (21) |
| 20 (6.1) | 139 (80) | 240 (138) | 290 (167) | 270 (155) | 240 (138) | 8 (5) |
|  | f’m = 3000 psi (20.7 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 10,300 psi (71.0 MPa), Type N mortar, orMin. brick unit strength 8250 psi (56.9 MPa), Type S or M mortar) |
| f/L = 0.05 | f/L = 0.10 | f/L = 0.15 | f/L = 0.20 | f/L = 0.25 | f/L = 0.30 |
| Arch Depth = 8 in. (203 mm) |
| 2 (0.61) | 1460 (839) | 2600 (1494) | 3410 (1959) | 3940 (2264) | 4270 (2453) | 4460 (2563) |
| 4 (1.2) | 740 (425) | 1350 (776) | 1750 (1005) | 1970 (1132) | 2060 (1184) | 2080 (1195) |
| 6 (1.8) | 500 (287) | 900 (517) | 1140 (655) | 1240 (712) | 1250 (718) | 1210 (695) |
| 8 (2.4) | 370 (213) | 670 (385) | 830 (477) | 870 (500) | 840 (483) | 790 (454) |
| 10 (3.0) | 290 (167) | 530 (305) | 640 (368) | 650 (373) | 610 (350) | 420 (241) |
| 12 (3.7) | 240 (138) | 430 (247) | 510 (293) | 510 (293) | 460 (264) | 44 (25) |
| 14 (4.3) | 200 (115) | 360 (207) | 420 (241) | 400 (230) | 230 (132) | 10 (6) |
| 16 (4.9) | 182 (105) | 310 (178) | 350 (201) | 330 (190) | 39 (22) | NP |
| 18 (5.5) | 160 (92) | 270 (155) | 300 (172) | 270 (155) | 9 (5) | NP |
| 20 (6.1) | 142 (82) | 240 (138) | 260 (149) | 230 (132) | NP | NP |
|  | Arch Depth = 12 in. (305 mm) |
| 2 (0.61) | 2130 (1224) | 3730 (2143) | 4850 (2787) | 5600 (3218) | 6100 (3505) | 6410 (3683) |
| 4 (1.2) | 1100 (632) | 1990 (1143) | 2610 (1500) | 2990 (1718) | 3210 (1844) | 3320 (1908) |
| 6 (1.8) | 740 (425) | 1350 (776) | 1750 (1005) | 1970 (1132) | 2060 (1184) | 2070 (1189) |
| 8 (2.4) | 550 (316) | 1010 (580) | 1290 (741) | 1420 (816) | 1450 (833) | 1420 (816) |
| 10 (3.0) | 440 (253) | 800 (460) | 1010 (580) | 1090 (626) | 1080 (621) | 1030 (592) |
| 12 (3.7) | 370 (213) | 660 (379) | 820 (471) | 870 (500) | 840 (483) | 780 (448) |
| 14 (4.3) | 310 (178) | 560 (322) | 690 (396) | 710 (408) | 670 (385) | 610 (350) |
| 16 (4.9) | 270 (155) | 480 (276) | 590 (339) | 590 (339) | 540 (310) | 132 (76) |
| 18 (5.5) | 240 (138) | 420 (241) | 510 (293) | 500 (287) | 450 (259) | 36 (21) |
| 20 (6.1) | 210 (121) | 380 (218) | 440 (253) | 430 (247) | 380 (218) | 8 (5) |
|  | f’m = 4000 psi (27.6 MPa), Ft = 53 psi (0.37 MPa)(Min. brick unit strength 11,500 psi (79.3 MPa), Type S or M mortar) |
| f/L = 0.05 | f/L = 0.10 | f/L = 0.15 | f/L = 0.20 | f/L = 0.25 | f/L = 0.30 |
| Arch Depth = 8 in. (203 mm) |
| 2 (0.61) | 1950 (1120) | 3470 (1994) | 4550 (2614) | 5260 (3022) | 5700 (3275) | 5960 (3424) |
| 4 (1.2) | 1000 (575) | 1800 (1034) | 2340 (1344) | 2630 (1511) | 2750 (1580) | 2770 (1592) |
| 6 (1.8) | 670 (385) | 1200 (689) | 1530 (879) | 1660 (954) | 1670 (960) | 1620 (931) |
| 8 (2.4) | 500 (287) | 890 (511) | 1110 (638) | 1170 (672) | 1130 (649) | 1050 (603) |
| 10 (3.0) | 400 (230) | 710 (408) | 860 (494) | 870 (500) | 820 (471) | 740 (425) |
| 12 (3.7) | 330 (190) | 580 (333) | 690 (396) | 680 (391) | 620 (356) | 146 (84) |
| 14 (4.3) | 280 (161) | 490 (282) | 570 (328) | 540 (310) | 480 (276) | 58 (33) |
| 16 (4.9) | 240 (138) | 420 (241) | 480 (276) | 450 (259) | 134 (77) | 25 (14) |
| 18 (5.5) | 210 (121) | 370 (213) | 410 (236) | 370 (213) | 58 (33) | 9 (5) |
| 20 (6.1) | 193 (111) | 320 (184) | 350 (201) | 310 (178) | 28 (16) | NP |
|  | Arch Depth = 12 in. (305 mm) |
| 2 (0.61) | 2840 (1632) | 4970 (2856) | 6470 (3717) | 7470 (4292) | 8130 (4671) | 8560 (4918) |
| 4 (1.2) | 1480 (850) | 2660 (1528) | 3480 (1999) | 4000 (2298) | 4290 (2465) | 4430 (2545) |
| 6 (1.8) | 990 (569) | 1800 (1034) | 2340 (1344) | 2630 (1511) | 2750 (1580) | 2770 (1592) |
| 8 (2.4) | 740 (425) | 1350 (776) | 1730 (994) | 1900 (1092) | 1940 (1115) | 1900 (1092) |
| 10 (3.0) | 590 (339) | 1080 (621) | 1360 (781) | 1460 (839) | 1450 (833) | 1380 (793) |
| 12 (3.7) | 490 (339) | 890 (511) | 1110 (638) | 1160 (666) | 1120 (644) | 1050 (603) |
| 14 (4.3) | 420 (241) | 750 (431) | 920 (529) | 950 (546) | 900 (517) | 820 (471) |
| 16 (4.9) | 370 (213) | 650 (373) | 790 (454) | 790 (454) | 730 (419) | 380 (218) |
| 18 (5.5) | 320 (184) | 570 (328) | 680 (391) | 670 (385) | 610 (350) | 138 (79) |
| 20 (6.1) | 290 (167) | 510 (293) | 600 (345) | 580 (333) | 510 (293) | 67 (38) |
| 1Values are in addition to self-weight, assumed to be 10psf/in. thickness (18.9 N/m2 /mm thickness)2Interpolation is permitted.3Segmental Arches with f/L>0.3 should be designed as equivalent semicircular arches with L = 2R.4NP = Not Permitted, excessive tension in arch |

**Table 4**

**Maximum Equivalent Applied Uniform Load – Semicircular Arches, lb/ft per inch of Arch Thickness (N/m per mm), Applied P = 0 lb (0 N)1,2**

|  |  |  |
| --- | --- | --- |
| Arch Span, ft (m) | f’m = 1200 psi (8.28 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 3000 psi (20.7 MPa), Type N, S, or M mortar) | f’m = 2000 psi (13.8 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 6200 psi (42.7 MPa), Type N mortar, orMin. brick unit strength 4950 psi (34.1 MPa), Type S or M mortar) |
| Arch Depth, in. (mm) | Arch Depth, in. (mm) |
| 8 (203) | 12 (305) | 8 (203) | 12 (305) |
| 2 (0.61) | 1950 (1120) | 2770 (1592) | 3260 (1873) | 4630 (2660) |
| 4 (1.2) | 930 (534) | 1460 (839) | 1560 (896) | 2450 (1408) |
| 6 (1.8) | 550 (316) | 930 (534) | 930 (534) | 1560 (896) |
| 8 (2.4) | 370 (213) | 640 (368) | 620 (356) | 1090 (626) |
| 10 (3.0) | 260 (149) | 470 (270) | 440 (253) | 800 (460) |
| 12 (3.7) | 170 (98) | 360 (207) | 170 (98) | 610 (350) |
| 14 (4.3) | 40 (23) | 280 (161) | 40 (23) | 480 (276) |
| 16 (4.9) | 11 (6) | 220 (126) | 11 (6) | 390 (224) |
| 18 (5.5) | NP3 | 162 (93) | NP | 162 (93) |
| 20 (6.1) | NP | 51 (29) | NP | 51 (29) |
| Arch Span, ft (m) | f’m = 3000 psi (20.7 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 10,300 psi (71.0 MPa), Type N mortar, orMin. brick unit strength 8250 psi (56.9 MPa), Type S or M mortar) | f’m = 4000 psi (27.6 MPa), Ft = 53 psi (0.37 MPa)(Min. brick unit strength 11,500 psi (79.3 MPa), Type S or M mortar) |
| Arch Depth, in. (mm) | Arch Depth, in. (mm) |
| 8 (203) | 12 (305) | 8 (203) | 12 (305) |
| 2 (0.61) | 4900 (2815) | 6950 (3993) | 6540 (3758) | 9270 (5326) |
| 4 (1.2) | 2350 (1350) | 3690 (2120) | 3140 (1804) | 4920 (2827) |
| 6 (1.8) | 1410 (810) | 2350 (1350) | 1880 (1080) | 3140 (1804) |
| 8 (2.4) | 940 (540) | 1640 (942) | 1260 (724) | 2190 (1258) |
| 10 (3.0) | 670 (385) | 1210 (695) | 900 (517) | 1630 (937) |
| 12 (3.7) | 170 (98) | 930 (534) | 470 (270) | 1250 (718) |
| 14 (4.3) | 40 (23) | 740 (425) | 134 (77) | 1000 (575) |
| 16 (4.9) | 11 (6) | 600 (345) | 62 (36) | 810 (465) |
| 18 (5.5) | NP | 162 (93) | 31 (18) | 470 (270) |
| 20 (6.1) | NP | 51 (29) | 14 (8) | 177 (102) |
| 1Values are in addition to self-weight, assumed to be 10psf/in. thickness (18.9 N/m2 /mm thickness)2Interpolation is permitted.3NP = Not Permitted, excessive tension in arch |

**Table 5**

**Maximum Equivalent Applied Uniform Load – Jack Arches, lb/ft per inch of Arch Thickness (N/m per mm), Applied P = 0 lb (0 N)1,2**

|  |  |  |
| --- | --- | --- |
| Arch Span, ft (m) | f’m = 1200 psi (8.28 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 3000 psi (20.7 MPa), Type N, S, or M mortar) | f’m = 2000 psi (13.8 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 6200 psi (42.7 MPa), Type N mortar, orMin. brick unit strength 4950 psi (34.1 MPa), Type S or M mortar) |
| Arch Depth, in. (mm) | Arch Depth, in. (mm) |
| 8 (203) | 12 (305) | 8 (203) | 12 (305) |
| 2 (0.61) | 690 (396) | 1580 (908) | 1170 (672) | 2650 (1523) |
| 3 (0.91) | 290 (167) | 690 (396) | 510 (293) | 1160 (666) |
| 4 (1.2) | 157 (90) | 370 (213) | 270 (155) | 640 (368) |
| 5 (1.5) | 90 (52) | 220 (126) | 166 (95) | 400 (230) |
| 6 (1.8) | 52 (30) | 147 (84) | 105 (60) | 260 (149) |
| 7 (2.1) | 28 (16) | 97 (56) | 66 (38) | 184 (106) |
| 8 (2.4) | 11 (6) | 63 (36) | 40 (23) | 130 (75) |
| 9 (2.7) | NP3 | 39 (22) | 21 (12) | 91 (52) |
| 10 (3.0) | NP | 20 (11) | 7 (4) | 63 (36) |
| Arch Span, ft (m) | f’m = 3000 psi (20.7 MPa), Ft = 20 psi (0.14 MPa)(Min. brick unit strength 10,300 psi (71.0 MPa), Type N mortar, orMin. brick unit strength 8250 psi (56.9 MPa), Type S or M mortar) | f’m = 4000 psi (27.6 MPa), Ft = 53 psi (0.37 MPa)(Min. brick unit strength 11,500 psi (79.3 MPa), Type S or M mortar) |
| Arch Depth, in. (mm) | Arch Depth, in. (mm) |
| 8 (203) | 12 (305) | 8 (203) | 12 (305) |
| 2 (0.61) | 1760 (1011) | 3980 (2287) | 2350 (1350) | 5310 (3051) |
| 3 (0.91) | 770 (442) | 1750 (1005) | 1030 (592) | 2350 (1350) |
| 4 (1.2) | 420 (241) | 970 (557) | 570 (328) | 1310 (753) |
| 5 (1.5) | 260 (149) | 610 (350) | 350 (201) | 820 (471) |
| 6 (1.8) | 170 (98) | 410 (236) | 230 (132) | 560 (322) |
| 7 (2.1) | 115 (66) | 290 (167) | 163 (94) | 400 (230) |
| 8 (2.4) | 77 (44) | 210 (121) | 114 (66) | 290 (167) |
| 9 (2.7) | 51 (29) | 157 (90) | 80 (46) | 220 (126) |
| 10 (3.0) | 31 (18) | 116 (67) | 54 (31) | 170 (98) |
| 1Values are in addition to self-weight, assumed to be 10psf/in. thickness (18.9 N/m2 /mm thickness)2Interpolation is permitted.3NP = Not Permitted, excessive tension in arch |

**DESIGN EXAMPLES**

**Example 1**

**Problem.** A residential builder is considering a series of (3) 8 in. (203 mm) deep, 3-5/8 in. (92 mm) thick, segmental arches above windows, each 3 ft (0.91 m) wide, with a 3-5/8 in. (92 mm) column of brick in between the arches (see Figure 10). The arches are within a brick veneer and carry no additional applied loads. Determine whether arches will work and what the minimum abutment distances are on each end of the arches. Determine whether semicircular or jack arches could be used instead.



**Figure 10**

**Design Example 1**

**Solution.** The geometry of each of the arches gives an f/L value of 0.139 and a radius, R, of 34.9 in. (886 mm). Thus, the arches can be considered minor segmental arches. Using only the triangular dead load above the arches, w is 3.02 lb/in. (0.53 N/mm) and the self-weight of 2.42 lb/in (0.40 N/mm), from Equation 4, the crown thrust, H, is 126.3 lb (562 N). The y-coordinates of the equilibrium polygon are checked using Equations 6 & 7 and found to be within the middle third throughout the length of the arch. Next, checking for sliding, Equation 8 is used to determine that the angle of application of the loads at the skewback (37.8º) minus the angle of the skewback (31.1º) is in fact less than the angle of friction (24º). Next, using Equation 10 we determine the normal force, N, at the skewback to be 158.7 lb (706 N). Lastly, the maximum compressive stress is determined from Equation 11 to be 10.9 psi (75.1 kPa). Provided the brick have a unit strength of at least 2100 psi (14.5 MPa), and Type N mortar is used, the allowable stress in the brick masonry is 400 psi (2.76 MPa). Therefore, the arch will work as designed.

In addition to verifying the arches, the abutments must be designed to provide sufficient thrust resistance. With the series of arches shown, the resultant forces between arches are equal and opposite meaning that there is zero horizontal load at the narrow columns of veneer between windows. Therefore, the horizontal loads of the three arches are reduced to only single arch reactions at the far left and far right abutments. Therefore, for abutment design purposes, using an H of 126.3 lb (562 N), f’m of 1200 psi (8.27 MPa) and n = 2, the minimum abutment length determined from Equation 2 is 1.16 in. (29.5 mm).

For semicircular arches in the same configuration, the equivalent segmental arch has an f of 10.6 in. (269 mm) and an L of 32.8 in. (826 mm). Because the f/L of the equivalent arch exceeds 0.15, it is considered a major segmental arch and the analysis becomes more stringent. First, by using a spreadsheet with 96 increments along the arch, from Equation 12, y0 is found to be 19.5 in. (495 mm). Likewise, using Equations 13 through 15, M = 1064 lb-in. (120.2 N-m), H = 108.8 lb (484 N), and V = 94.8 lb (422 N). Then, using Equations 17, 20, and 21, the values of Mx, Nx, and Qx can be determined at the springing as 34.9 lb-in. (3.9 N-m), 143.2 lb (637 N), and 18.0 lb (80.1 N), respectively. Next, using Equations 22 and 23, the compressive stresses at the extrados and intrados are found to be 4.0 psi (27.6 kPa) and 5.8 psi (40.0 kPa), respectively. The minimum abutment length for the semicircular arches becomes 1.0 in. (25.4 mm).

For jack arches, the calculations in Figure 9 give a k of 3 in. (76 mm) and an f of 3/8” (9.5 mm). Equations 26 and 27 are used to determine H = 489 lb (2177 N) and V = 145 lb (645 N). From Equation 28, it is seen that the angle of the load at the skewback (16.5º) minus the angle of the skewback (20.6º) is less than the angle of friction (24º). Lastly, the compressive stresses are determined at the midspan and skewback using Equations 28 and 29 to be 33.8 psi (233 kPa) and 71.6 psi (494 kPa), respectively. For the skewback arches, the minimum abutment length is 4.5 in. (114 mm).

**Example 2**

**Problem.** For the home of Example 1, the builder wishes to put an 8 in. (203 mm) deep, 3-5/8 in. (92 mm) thick arch above a single car garage door with an opening width of 10 ft (3.0 m), as shown in Figure 11. Both a jack arch and low-rise segmental arch are to be considered.



**Figure 11**

**Design Example 2**

**Solution.** Starting with the segmental arch, the first step is determining the loading. Because there is only 32 in. (0.81 m) of masonry above the opening, there is insufficient brickwork to provide arching action. Therefore, the total weight of the veneer must be applied to the arch. This gives a uniform load of approximately 7.0 lb/in. (791 N/m). Using the same spreadsheet analysis as for Example 1, M = 16,930 lb-in. (1910 N-m), H = 2145 lb (9.55 kN), and V = 423 lb (1.88 kN). At the Skewback, Mx = 26.8 lb-in. (3.0 N-m), Nx = 2190 lb (9.75 kN), and Qx = 4.7 lb (20.9 N). The compressive stresses at the extrados and intrados are 74.7 psi (515 kPa) and 76.1 psi (525 kPa), respectively. The minimum abutment dimension is 19.7 in. (500 mm).

For the jack arch, k = 10 in. (254 mm) and f = 1.25 in. (32 mm). The total weight of the brick above the opening gives a w of approximately 17.4 lb/in (3.1 N/m). The resulting thrust, H, is 11,700 lb (80.6 kN). The difference in angles between the skewback (51.3º) and the line of application of forces at the skewback (5.1º) is greater than the angle of friction (31º). However, the sign of the difference indicates that the arch is tending to move upwards along the slope of the skewback rather than downwards toward the opening, and therefore is held in place by the brick above and the abutment. The compressive stresses at the skewback and midspan are computed to be 1520 psi (10.5 MPa) and 810 psi (5.6 MPa), respectively, both of which exceed the allowable stress. If a much higher strength masonry was constructed to accommodate the jack arch, the minimum abutment length would be 12.8 in. (325 mm).

**Example 3**

**Problem.** For a multi-family residential project, the builder wishes to place a pedestrian plaza above the entrance to the parking garage, with load-bearing semicircular brick arches providing the entrance and support for the plaza, as shown in Figure 12. The opening for each arch is 12 ft (3.7 m), but if feasible a single 20 ft (6.1 m) arch might be preferred. The plaza spans 20 ft (6.1 m) to columns within the garage, meaning 10 ft (3.0 m) of the plaza rests on the brickwork. If the live load on the plaza is 200 psf (9580 N/m2) and the dead load of the plaza slab is 100 psf (4790 N/m2), what thickness and depth must the arch be to accommodate the loading? Assume f’m = 4000 and PCL Type S mortar.



**Figure 12**

**Design Example 3**

**Solution.** The first step in the design is deciding the applied load. The plaza load converts to a linear load of 3000 lb/ft (43.8 kN/m). From Table 4 using f’m=4000 psi (27.6 MPa) and Ft = 53 psi (0.37 MPa), for a span of 12 ft (3.7 m), the allowable load for an 8 inch (203 mm) deep arch is 470 lb/ft per inch of thickness (270 N/m per mm) and for a 12 inch (305 mm) deep arch is 1250 lb/ft per inch (575 N/m per mm). For the applied load, the shallower arch would need to be 6.4 in. (163 mm) thick and the deeper arch would need to be 2.4in. (61 mm) thick. For the 20 ft. (6.1 m) span, Table 4 gives an allowable load for the 12 inch (305 mm) deep arch of 177 lb/ft per inch (102 N/m per mm). This corresponds to a minimum thickness of 16.9 in. (429 mm), likely not feasible.

Once the arch size is chosen, the thrust, H, needs to be determined and suitable abutments, accommodating load along the entire thickness of the arch, provided. Note also that though not appearing in Table 4, using the equations and methods provided above, a 16 in. (406 mm) deep arch, 2 wythes thick would carry the imposed plaza load with a required abutment width of 122 in. (3.1 m)

**Example 4**

**Problem.** An industrial warehouse, built using loadbearing brick masonry, 7-5/8” (194 mm) thick, uses loading dock doors with segmental arches above, as shown in Figure 13. It is desired to place a beam above some of the doors whereby a 4 ton hoist could be used to help unload flatbed trucks. The beam would bear 32 in. (813 mm) above the crown of the arches, where the mezzanine floor also bears. Is the addition of the hoists and beams permitted? The load from the mezzanine floor is 2000 lb/ft (29.2 kN/m). Assume f’m = 3000 and PCL Type S mortar.



**Figure 13**

**Design Example 4**

**Solution.** The first step is to determine the appropriate loading on the arch. The geometry of the arch gives an f/L ratio of 0.3 and an R value of 68 in. (1.7 m). Therefore, the line load from the mezzanine and point load from the beam are applied at a distance 1.64R above the center point of the arch and must be considered. The load P is taken at worst case, with the full 8000 lb (35.6 kN) resting at the wall. Using the analysis for major segmental arches and including the weight of the masonry above, M = 622,600 lb-in (70.3 kN-m), H = 18,410 lb (81.9 kN) and the maximum compressive stress is 1120 psi (7719 kPa), exceeding allowable. Even were the masonry strength increase to 4000 psi (27.6 MPa), the maximum tensile stress of 470 psi (3240 N) far exceeds the allowable stress in the brickwork.

There are two options the warehouse has for installing the beam. The first would be to limit the maximum point load at the arch to approximately 910 lb (4.1 kN) by down-sizing the hoist or limiting the load location so that other supports carry a portion of the hoist capacity. The second option is to spread the load of the beam along the length of the arch. Raising the beam to a height of 2.4R above the center of the arch would allow arching action to spread the load appropriately. This corresponds to placing the beam a distance of 83.2 in. (2.1 m) above the crown of the arch.

**SUMMARY**

Masonry arches have long been used as structural elements able to convert vertical loads along the arch to vertical reaction and horizontal thrust at abutments. The design of these elements, whether used in lightly loaded veneers or heavily loaded commercial loadbearing walls, is governed by straightforward principles of friction and equilibrium. Equations have been developed for the design of the vast majority of arches commonly in use in modern construction: segmental arches, semicircular arches, and jack arches. The use of these equations and design procedures are limited in some cases, but in those cases, other tools, such as finite element analysis are available to the designer.

*The information and suggestions contained in this* Technical Note *are based on the available data and the experience of the engineering staff and members of the Brick Industry Association. The information contained herein must be used in conjunction with good technical judgment and a basic understanding of the properties of brick masonry. Final decisions on the use of the information discussed in this* Technical Note *are not within the purview of the Brick Institute of America and must rest with the project architect, engineer and owner.*

**REFERENCES**

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