Vaulted Shell Structures Design Guide – Basic Considerations

Design Topics:

Why choose a vault shape?
- Clear-span; Safety; Visibility

What do you need to consider?
- Support; Profile; Cladding

Putting it in place.
- Construction

Vault profiles are achieved using many different techniques. A vault is a single curvature structure that can be described as a section of a cylinder up to and including a hemisphere or semi-circular profile. These are often referred to as “barrel vaults”. Vaults also include structures that utilize a few other profiles that involve the use of a ‘keystone’ element. This ‘keystone’ is the critical element that balances the vault and keeps it from collapsing in on itself. The vault structures that employ this strategy will not be discussed here. Their application is mostly found in masonry archways, interior double intersecting vaults and ancient bridge support systems. For further information, a study of ancient structures and masonry methods should be undertaken. We are going to discuss the modern incarnation of the vault that utilizes the thin shell method and variants thereof that employ bottom chord ties, and trusses.

Vaults behave in a similar way to their namesakes. They leap from one side of an opening to the other providing a clear-span structure that relies upon the ends for its sole support. The profile follows a curved profile and is often constructed of rolled sections or provided with segmented structure and fixed joints. Joint fixity (stiffness) is achieved through welding or using a bolted connection producing a moment-resistant (non-rotating) connection detail. This keeps the vault from collapsing. If a single joint were allowed to rotate, it would become a hinge point for the entire structure, and allow the structure to fold in onto itself resulting in failure.

Vaults are a stable structure for uniform load conditions. They share some of the same benefits of other shell structures. Vaults distribute load across a larger area to minimize the effects of local loading. The load transfers itself along the surface to the supports producing...
mostly axial force for the interior elements. This principle works well with rolled sections and with segmented structures. Segmented structures will have the added effects of bending contributing to the members at the perimeter and curve inflection points. Unbalanced loading and lateral wind pressures will produce maximum bending. The structure will deflect vertically and laterally to accommodate the loading. The deflected profile will resemble an ‘S’ shape on its side. It is the unbalanced load conditions that will provide the greatest opportunity for structural failure through global buckling. It is important to perform an analysis for any unbalanced load condition such as drifting snow, heavy lateral wind loads, or unbalanced live loading. The bearing (vertical) load and thrust (lateral) forces at the support locations will depend on the rigidity (stiffness) of the supports. Connecting to the middle of a beam will produce a less rigid connection than one that has a beam connected in a ‘T’ configuration at the support location. It is important to provide a uniform rigidity along each of the support edges to ensure the vault behaves correctly and does not concentrate forces unnecessarily at a single support point. To reduce this effect, ties (bottom chord elements) are useful in providing an adjustable support scheme through tensioning/relaxation. The use of cables will require an engineer experienced in their design and an installer familiar with the tensioning process. The clear-span solution of the vault offers benefits in addition to the many design considerations.

The vault provides for an unobstructed visual element that brings natural daylight in to atrium and public spaces. Vaults are used for roof structures that often include smaller skylights embedded into the surface. This structural system is used a great deal for athletic venues that include basketball arenas, football practice fields, and natatoriums. Vault structures that are shell structures are often skylights, canopies, transit station roofs, and curtainwall structures. The applications of this structural system are many.

The types of structures that produce a vault profile include the following:

- Single layer shell
- Trussed arch
- Single layer shell with bottom chord ties (like stringing an archery bow)
- Spaceframe arch
- Trusses with top chord arch

The structural behavior of each is different because each uses a different structural mechanism for transferring loads to the support structure. In brief, they are as follows:
- Single layer shell – Surface members from linear elements to arch elements; thrust taken at support elements
- Trussed arch – linear elements to trusses down to truss support; thrust taken at support elements
- Single layer shell with bottom chord ties - Surface members from linear elements to arch elements; thrust taken at chord ties
- Spaceframe arch – Top and bottom chord take bending into axial force, transfer to supports; minimal thrust
- Trusses with top chord arch – Behaves as typical truss, top/bottom chords take axial force; bearing at supports, minimal thrust

The profile for the vault is key and the prime factor in determining thrust and chord forces. As a general rule: the higher the profile, the less thrust at the supports. This can be a critical decision when working with the primary structural steel consultant or concrete superstructure. The selection of which system to use is also critical when doing roof retrofit work or when adding a large skylight to an existing roof structure. To reduce the impact of the vault structure, it is important to select the right cladding material to provide the desired visual impact, thermal performance and keep the weight-per-square foot down.

Cladding options are many and depend upon the intent, performance characteristics desired, acoustic demands, and budget. Vault structures accept all traditional roof cladding materials. Additionally, glass, translucent panel assemblies, and composite metal panels can be applied to provide aesthetic and performance characteristics. The challenge will be to ensure that the cladding product will accommodate the vault deflection for both uniform and unbalanced loading conditions.

Additional considerations will include providing an allowance for the thermal movement of the frame along the linear edges. Some additional framing may need to be introduced if end walls are constructed as part of the vault structure. A structural engineer will be able to accommodate these elements and provide the necessary thermal and structural strategies.

You will also need to consult an engineer for the construction of vaulted shell structures. They will require shoring and bracing to ensure that they are installed in the proper shape. This can be accomplished with temporary cable
ties or other bracing elements such as bar or angle elements. Also, it might be possible to either erect in place with scaffolding and shoring, or to construct the structure at ground level and lift it in to place. The options depend upon the size, span, and weight of the structure under consideration.

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