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# Investigation of a Stone Arch Bridge

**Figure 1. Upstream view of the Winter Street Bridge over the Sudbury River. Bridge built in 1700s. 1995 photo. Causeway extends from both ends of the bridge. Stone wall and banking in left foreground added in the 1870s.**

The stone arch bridge is located on Winter Street in Framingham, MA, where it crosses the Sudbury River. The bridge is part of a causeway connecting the high ground on both sides of the Sudbury River. The bridge and causeway were built in the 1700s. The causeway consists of two dry stone masonry retaining walls with fill between them. Where the causeway crossed the original river channel, a two-span dry stone masonry arch bridge was constructed. In 1971 a separate foot bridge was erected close to the downstream side of the causeway, and at that time the dry stone masonry arches of the bridge were pressure grouted and the exposed surfaces of the arch barrels and spandrel walls were gunited.[1]

Figure 1 is a photo of the upstream side of the bridge as it existed in 1995. Figure 2 *(page 2)* is a photo of the downstream side. Figure 3 shows the underside of one of the arch barrels. Figures 4, 5, and 6 *(page 3)* show a plan, a longitudinal cross-section, and a transverse cross-section of the bridge.

The bridge was investigated for load capacity and condition in 1977 by Rubin M. Zallen Associates (a predecessor of Zallen Engineering). There were some available sketches of the bridge dated in 1930; however, they showed little detail and were not adequate for a structural evaluation. Thus, detailed field observations and measurements were undertaken to determine the geometry of the bridge and to determine its condition.

An arch is of such a form that it resists external load principally by internal compression. This compression acts parallel to the (curved) longitudinal centerline or axis of the arch. Since masonry construction is strong in compression and weak in tension, it is a suitable material for arches. However, there is also internal bending of the arch barrel, which acts with the axial com-

*Continued on page 2*

**See Notes for Non-Engineers on page 2.**
**See history of bridge and causeway on page 4.**

## Notes for Non-Engineers

1. The generic term for *gunite* is *shotcrete*. In the shotcrete process, concrete is sprayed on and adheres to a properly prepared surface.

2. In analysis, a hinge is assumed to exist after significant cracking, which changes the structural character of the arch.

3. For a more detailed explanation of arch action, See Issue No. 15 of *Forensic Engineering in Construction*.

4. The ratings are in accordance with the criteria of the American Association of State Highway and Transportation Officials. Three rating vehicles were used: a Type H truck which has a single rear axle and a 14 foot wheelbase; a Type 3 truck which has two rear axles spaced at 4 feet on center, and a spacing between the front axle and 1st rear axle of 15 feet; and a Type 3S2 truck which is a semi-trailer truck with double axles at the rear of the tractor and at the rear of the trailer.

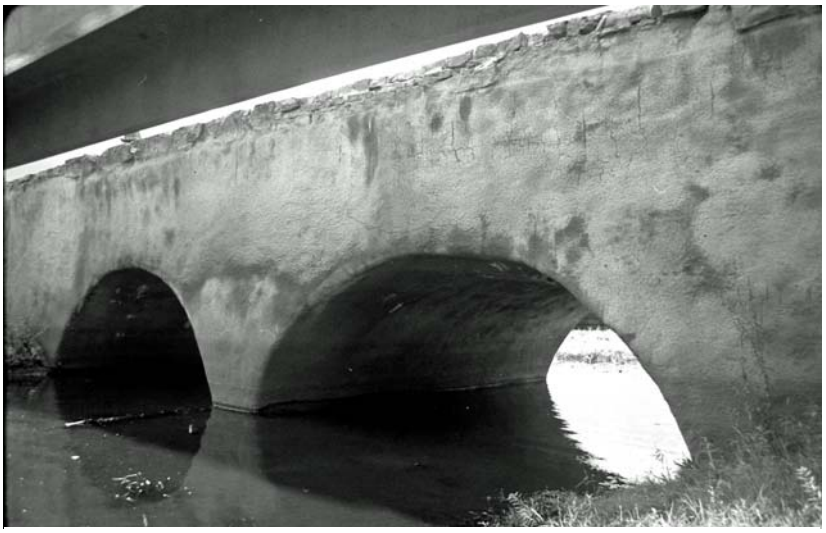

**Figure 2. Downstream side of the Winter Street Bridge as it appeared in 1977. The bottom of the footbridge can be seen in the upper left foreground.**

**Figure 3. View of bottom of one of the arch barrels. 1977 photo.**

pression, and which can lead to a net tension at the top or bottom face of the arch and cracking of the arch.

For analysis, tensile strength is ignored since it is too low to have a significant beneficial effect. Thus, incipient tension at a cross-section through the arch barrel is assumed to initiate cracking of the arch at that cross-section. As the cracking progresses, the sides of the crack rotate away from each other and gradually form a "hinge" which leads to a redistribution of the

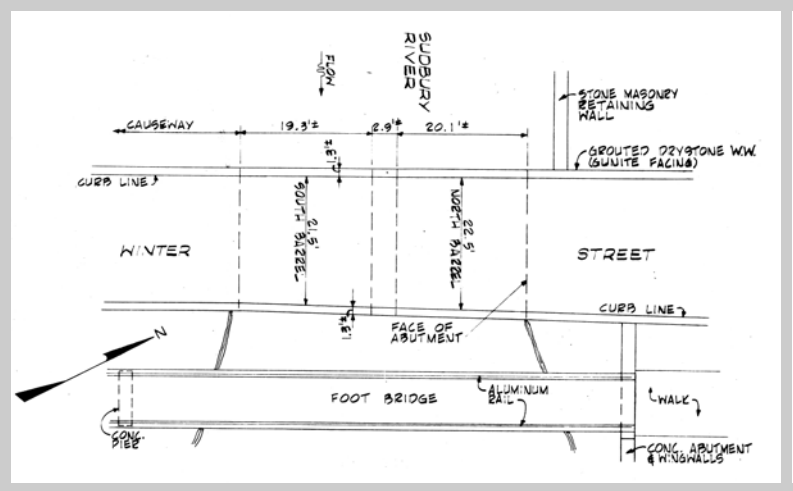


**Figure 4. Plan of the Winter Street Bridge**

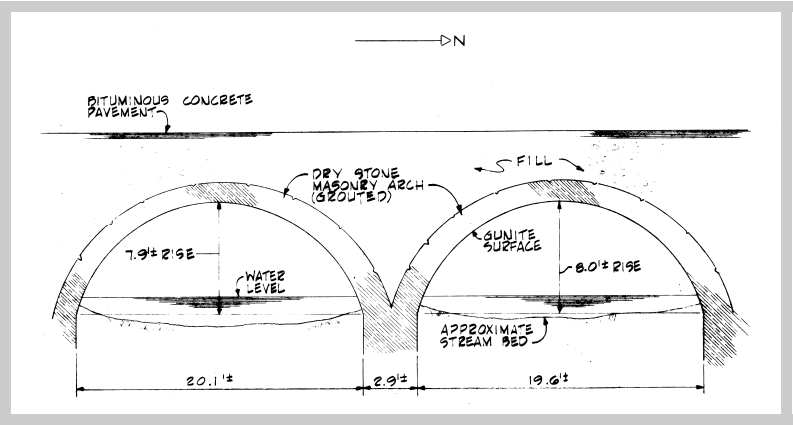


**Figure 5. Longitudinal section through the Winter Street Bridge.**

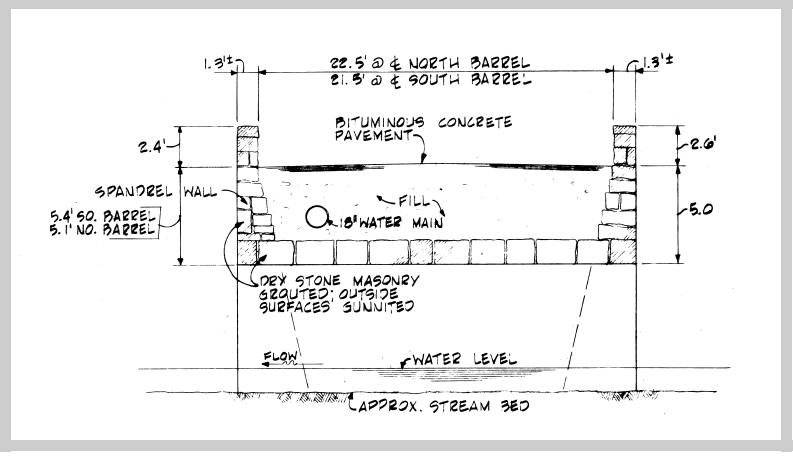


**Figure 6. Transverse section through the Winter Street Bridge, taken through the crown of the arches.**

(compressive) stresses throughout the arch. The analysis of the Winter Street Bridge arches was approached on a global basis, in which an internal force distribution is sought throughout the arch which will be in equilibrium with the applied loads, and in which the resulting stresses in the masonry do not exceed the compressive strength of the masonry. The "hinging" is accounted for in the analysis.[2] The maximum applied load was determined from these conditions.[3]

There is a limit to the number of "hinges" that can form beyond which the arch becomes unstable and collapses. We did not know the extent of the abutments (supports), and thus, in the analysis, we assumed that the abutments are "hinged;" i.e. cannot resist any bending. The next hinge that would likely form is at the crown (cracking at the bottom of the arch). If another hinge forms, the arch would collapse.

The bridge was in good condition at the time of the investigation (1977). Load ratings[4] were established for the bridge, which were 5 tons for a Type H truck, 9 tons for a Type 3 truck, and 14 tons for a Type 3S2 semi trailer truck. No truck traffic is permitted on this bridge, so the bridge and causeway were adequate for the permitted traffic.

- Principal Rubin M. Zallen lead the investigation of this bridge.

Forensic Engineering in Construction® is published by Zallen Engineering, 1101 Worcester Road, Framingham, MA 01701. Comments are welcome. Please direct comments to Rubin M. Zallen, P.E., by telephone at 508-875-1360 or by e-mail at rmzallen@zallenengineering.com.

# History of Winter Street Bridge and Causeway

In Colonial times, methods for building roadways over rivers were limited. One of the methods was to build a causeway across the flood plain of a river and to build a stone arched bridge at the location of the river channel. This method was used to cross the Sudbury River at Winter Street.

The original causeway and bridge were built in the early 1700s . The arches were built of dry stone (i.e. no mortar was used), and the spandrel walls of the bridge (the side walls) and the retaining walls of the causeway were also built of dry stone. The top of the arches, and the causeway, were filled with soil up to the road surface. There was no paving. Photo 7 shows what the roadway looks like today (2008).

In 1877, the Boston Water Works Commission constructed a dam across the Sudbury River, just west and upstream of the causeway, and constructed an underground aqueduct just south of the south end of the causeway. See Photos 7 and 8. The dam is known as Dam No. 1, and is one of three dams built to create reservoirs for water for the City of Boston. The aqueduct is known as the Sudbury Aqueduct.

When the dam was built, a new river channel and bridge was cut through the causeway near the south end. See Photo 8.

In 1930 or thereafter the Town of Framingham installed an 18" water main on Winter Street which required the raising of the road grade over the stone arch bridge and causeway (see Figure 6), and required a new steel beam and concrete bridge to be built in place of the 1877 bridge at the south end of the causeway.

In 1971 or immediately thereafter, a separate foot bridge was erected across the Sudbury River flood plain a few feet downstream (south) of the causeway. At that time, the dry stone masonry of the arch barrels and spandrels were pressure grouted and the exposed surfaces of the arch barrels and spandrels were gunited.

**Photo 7. Causeway looking south. Stone arch bridge is on the near end of the causeway. The dam is to the right and the footbridge is to the left.**

**Photo 8. View of causeway looking east from top of spillway of dam. The bridge at the south end of the causeway can be seen in the right background.**