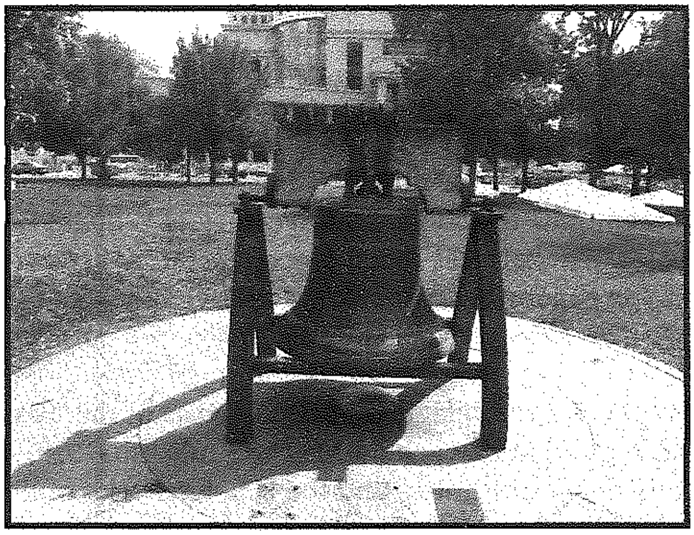
Report:

Investigation of Liberty Bell Replica, Denver, Colorado



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BACKGROUND

The original 1751 Liberty Bell was purchased by the Pennsylvania General Assembly to commemorate the 50-year anniversary of William Penn's 1701 Charter of Privileges; that bell was recast twice; the recast bell eventually could not be rung due to an expanding crack that is believed to have occurred when the bell was rung on Washington's Birthday in 1846.

The Liberty Bell replicas were designed in 1950 as part of the "Save For Your Independence" savings bond drive, held May 15 - July 4th, 1950. Each state (48, at the time), the District of Columbia, and the U.S. territories of Puerto Rico, Hawaii, Alaska, and the Virgin Islands, received a replica bell, which was then transported through its state or territory as part of the savings bond campaign. Although the replica bells cast by Paccard Foundry, of Annency-le-Vieux were commissioned by the U.S. Treasury, several private companies funded the project (each bell cost an estimated $2200). The replica bells were mounted on wooden yokes to allow them to be rung; plans for the two dozen hand-forged metal "gudgeons," "canons" and other hardware that hold the 2,100-pound bells in place are thought to be kept at the National Archives.

The Liberty Bell Replica in Lincoln Park, Denver, Colorado (the Bell) is currently showing signs of distress. Anthony & Associates, Inc. (A&A) was contacted by Ms. Sue Johnson of the Mount Rosa Chapter of the Daughters of the American Revolution (DAR) about the condition of the Bell. After conducting a brief site visit to the Bell, A&A was asked to submit a proposal for conducting an investigation and providing preservation options for the Liberty Bell Replica.

Several professionals have previously examined the Bell but have come to different conclusions regarding the condition and proper treatments to ensure that the Bell remains as a historic fixture in Lincoln Park for decades to come. In order to determine suitable repairs and preservation options for the Bell, it is necessary to first understand how the Bell is supported and whether the current support system has deteriorated and is no longer adequate. This first step is the purpose of the current investigation.

It should be noted that the National Park Service - National Center for Preservation Technology and Training (NCPTT) supported a portion of this work. The use of digital radioscopy (low-energy portable x-ray technology) provided a better understanding the deformation and conditions within the Bell. This information has not been collected on any other replica and is useful not only to this investigation but also for the analysis and preservation of other Liberty Bell replicas.

SCOPE OF WORK

The focus of this work was to develop a better understanding of the structural support of the Bell. The wood and steel components currently support the weight of the Bell but are showing signs of weathering and distress. It is not known whether the current support system can adequately support the Bell over time, particularly if the intent is to be able to ring the Bell on historic occasions.

The scope of work includes:

- Inspecting the Bell for wood and/or metal deterioration.
- Identifying the wood species of the wood yoke.
- Conducting a structural analysis of the Liberty Bell Replica support frame.
- Providing preservation options for ensuring the structural integrity of the Bell.

WOODEN YOKE INVESTIGATION

Anthony & Associates assessed the condition of the wooden yoke to determine wood species, identify the presence of any defects or deterioration that might affect the long-term performance of the Bell, and provide material input for the structural analysis. A&A also coordinated the radiographic investigation conducted by Logos Imaging LLC of Loveland, Colorado (an in-kind donation) to assess the condition of the threaded rods and straps embedded in the wooden yoke.

A small wood sample was removed to identify wood species. The species was identified as white oak (*Quercus spp.*). Identifying wood species makes it possible to determine material properties for conducting a structural analysis and to identify compatible material for repairs.

Visual inspection, probing, moisture content measurements, and resistance drilling were used to determine the presence and extent of any wood deterioration at specific locations on the yoke (Figure 1). Visual inspection enables detection of external wood decay fungi or insect activity as determined by the presence of decay fruiting bodies, fungal growth, insect bore holes or wood substance removed by wood-destroying insects.

Resistance drilling is a quasi-nondestructive technique for determining the relative density of wood. It is best suited for determining internal problems in timber, like the yoke, that does not show obvious signs of deterioration, such as surface decay. Any internal void or early stage of decay at the location drilled can be detected by determining the relative density of the wood. The relative density is printed on a strip of paper as a small diameter needle penetrates the wood. The results of the resistance drilling are presented in Table 1.

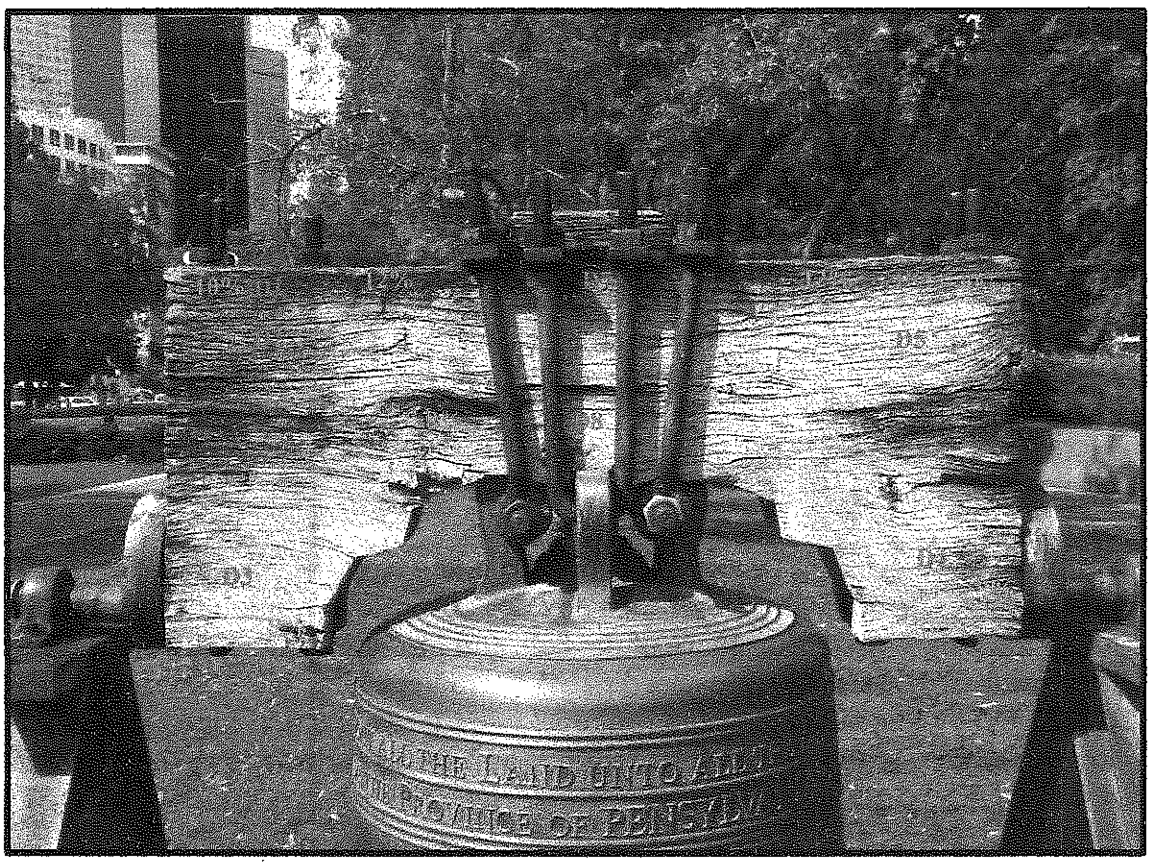


Figure 1. Liberty Bell Replica, Denver, Colorado. Drilling locations are marked in red, moisture contents in blue.

Prolonged exposure to moisture can cause excessive shrinkage or swelling, checking, loose connections, and decay in wood. Moisture content measurements can identify conditions favorable for the growth of wood-decay fungi. Generally, if the moisture content is less than 20 percent wood-decay fungi are unable to grow. Moisture contents from 20 to 30 percent indicate areas of concern where sufficient moisture is present for fungi to grow but not sufficient to indicate advanced decay. Moisture contents above 30 percent are often an indication of advanced decay with internal voids and / or surface deterioration. Moisture content measurement readings and locations are shown in Figure 1.

Table 1. Results of Resistance Drilling, Liberty Bell Replica, Denver, CO

Drilling Number	Face	Location	Drilling Direction	Comments
D1	South	4" from west, 2" from top	S-N	2" intermittent internal voids
D2	South	4" from west, 4" from top	S-N	less than 1/2" intermittent internal voids
D3	South	4" from west, 3" from bottom	S-N	no void
D4	South	4" from east, 3" from bottom	S-N	no void
D5	South	4" from east, 4" from top	S-N	1/2" internal void
D6	South	4" from east, 2" from top	S-N	3/4" internal void
D7	South	mid-width, 2" from top	S-N	less than 1/2" internal voids
D8	South	mid-width, 2.5" from bottom	S-N	no void

In addition to the wood assessment, digital radioscopy was used to examine the condition of the threaded rods and straps that were embedded in the wooden yoke and were, therefore, not accessible for visual inspection. The radioscopic examination involved taken images (radiographs) of the entire area of the yoke using the Logos Imaging Neos System. Figure 2 shows the setup for taking an image of the upper right corner of the yoke. The x-ray source was placed approximately 2 ½ feet from one face of the yoke and the imaging plate was placed as close to opposite face of the yoke as possible (allowing for bolt heads and other objects that prevented placing the imaging plate flush against the wood.

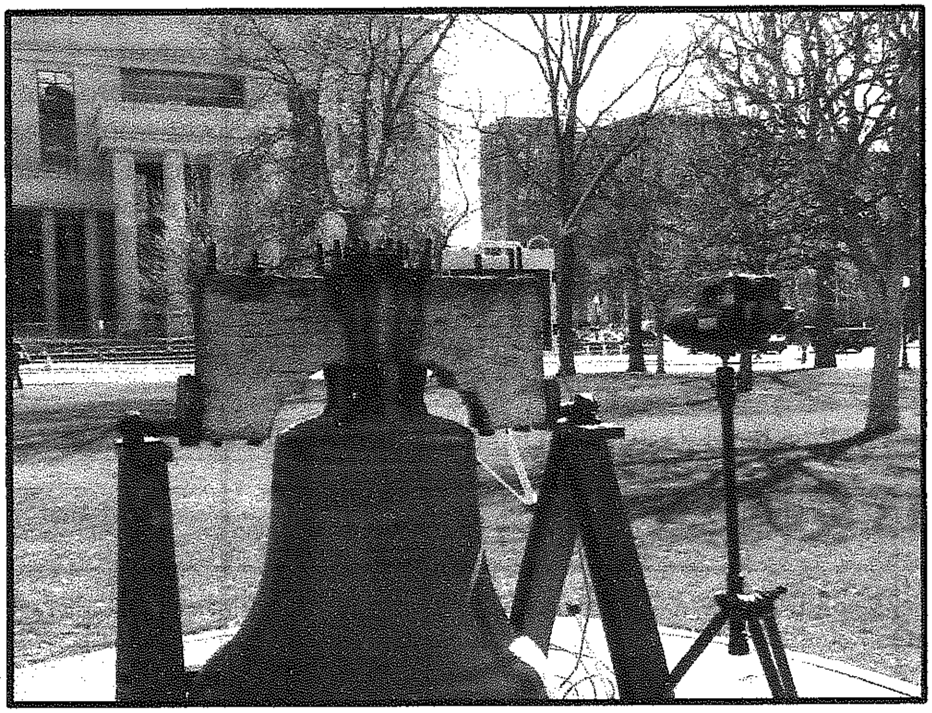


Figure 2. Digital radioscopy setup showing the x-ray source in the foreground and the imaging plate (barely) visible behind the upper right corner of the yoke.

The radiograph of the upper right corner of the yoke shows that the steel rods are in good condition (Figure 3). This is illustrated by the relatively parallel edges of the rods indicating that corrosion has not reduced the cross section. The radiograph of the lower right corner of the yoke shows minor surface corrosion of the two vertical rods, as indicating by the darker areas adjacent to the rods (Figure 4). This corrosion was observed on other rods, typically near the exposed end grain of the wooden yoke where moisture is absorbed into the wood. The surface corrosion may make it somewhat difficult to remove the rods for cleaning during repair of the yoke. Care should be taken to not forcefully remove the rods and risk splitting the wooden yoke. It should be noted that also visible in Figure 3 is the steel ring that is attached to the axle; it is in good condition.

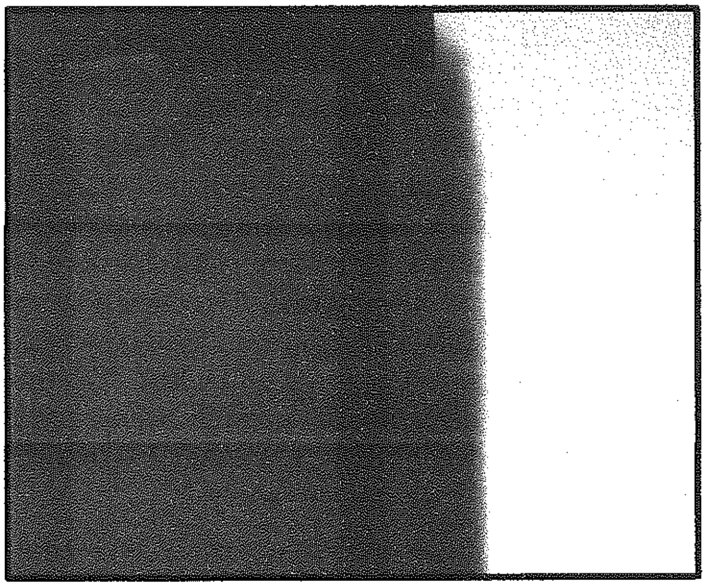


Figure 3. Radiograph corresponding to the setup shown in Figure 2. Note the sharp, parallel edges of the vertical steel rods, indicating no loss of cross section due to corrosion.

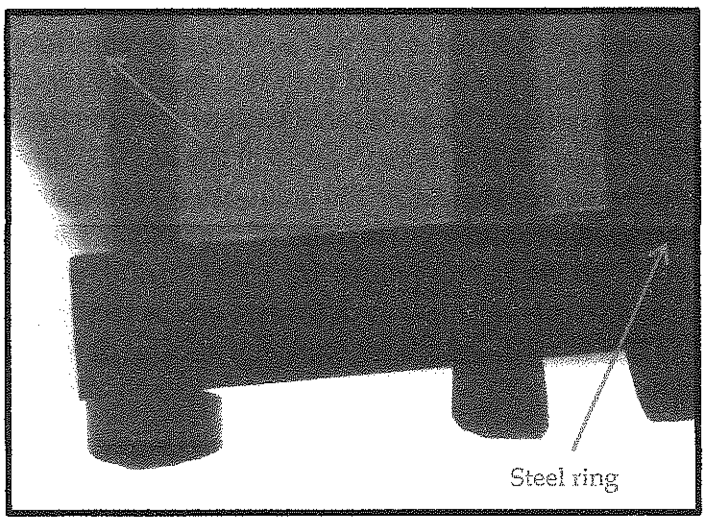


Figure 4. Radiograph corresponding to the area directly below the position shown in Figure 2. Note the dark staining adjacent to the steel rods due to rust accumulation.

Based on the investigation of the wooden yoke, the wood, steel rods, and steel straps are in good condition with minor deterioration due to wood decay adjacent to the metal strap at the top of the yoke, surface weathering of the wood (which produces the silver-gray patina), and minor surface corrosion on some of the steel rods embedded within the yoke. These conditions indicate that there is no need to replace the wooden yoke.

STRUCTURAL ANALYSIS

Atkinson-Noland & Associate (ANA) conducted a site visit to the Liberty Bell Replica in Denver to obtain detailed measurements of the bell support structure. Subsequently, ANA conducted a finite element (FE) analysis of the support structure of the Liberty Bell Replica. Using a finite element program, a computer model of the existing structure is created and the behavior of the supporting frame under the weight of the bell is simulated. The main objective of the analysis was to evaluate the original design of the support structure and investigate what caused the excessive sagging of the Bell. The final goal was to determine whether the existing structure has enough strength to support the Bell. This section of the report describes the finite element model, basic assumptions, and results of the finite element analysis.

Background

ANA conducted a site visit to the Liberty Bell Replica in Denver to obtain detailed measurements of the Bell support structure and evaluate the overall materials condition. The wood yoke and the steel connections show signs of deterioration due to weathering but are in fair-to-good condition. The steel support frames are mounted in concrete and are in good condition.

The main structural concern is associated with the sagging of the Bell, which likely prompted the installation of additional supports below the Bell. Some of the sagging may be related to the deterioration of the wood. However, the primary cause of sagging appears to be the connection failure at where the axles bear on the support frame (Figure). The base of the yoke is supported by a steel bar that cantilevers from the bearing assembly. The cantilever bar is connected to the yoke by through-bolts. Excessive deformations in the hinge connection of the bearing assemblies have caused both axles to shift out of alignment resulting in excessive sagging.

Figure 5. Connection failure at bearing. Both axles have shifted out of alignment resulting in the sagging of the support structure.

Finite Element Analysis

A static analysis was conducted to evaluate the original design of the support structure. Stresses and deformations in the yoke and the steel components were evaluated and compared to material strengths to evaluate the margin of safety of the structure.

Finite Element Model

A 3D model of the support structure was created using a finite element program. The geometry is shown in Figure and includes all the main components of the structure. In the computer model, the structure is divided into small elements that are connected to each other. Three-dimensional solid elements were used to model the wood yoke and the steel hardware. Bar elements were used to reproduce the steel rods while special surface elements, called interface elements, were employed to model the contact between steel and wood, allowing the two materials to move independently. Yield strength of 36 ksi and elastic modulus of 28,000 ksi were adopted for the steel. Material properties used for the yoke are summarized in Table 2. Both green and dry properties of White Oak were used in the analysis to represent the behavior of the wood yoke under saturated (green) and dry (12% moisture content or less) conditions. The estimated weight of the Bell is approximately 2080 lb. This load is equally divided among the ten nuts connecting the bell to the top steel plates.

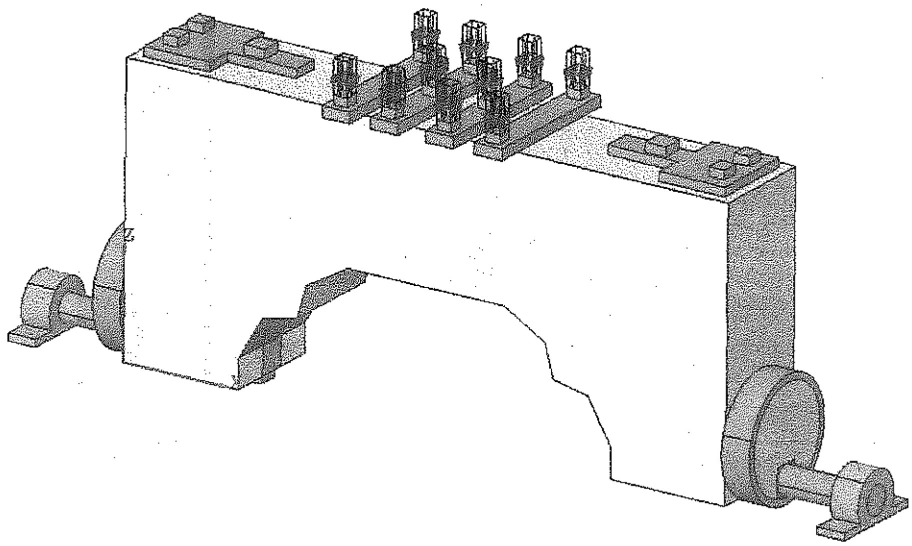


Figure 6. 3D Finite element model of bell support structure. Vertical loads at the top of the structure produced by the bell weight are also visible.

Table 2. Wood (White Oak) Material Properties used for Analysis.

		Wood Moisture Content	
		Dry (12% moisture)	Green (saturated)
Density (pcf)		47.5	73.4
Tensile strength perp. to grain (psi)		800	770
Compressive strength perp. to grain (psi)		1,070	670
Shear strength parallel to grain (psi)		2,000	1,250
Elastic modulus (psi)	E_L	1,780,000	1,250,000
	E_R	290,140	203,750
	E_T	128,160	90,000
Shear modulus (psi)	G_{LR}	650,100	456,540
	G_{RT}	89,660	62,960
	G_{TL}	61,850	43,430
Poisson's ratio	ν_{LR}	0.369	0.369
	ν_{RT}	0.499	0.499
	ν_{TL}	0.036	0.036

L: longitudinal (X); R: radial (Y); T:tangential (Z).

Material continuity between the cantilever bar and the bearing assembly provides the flexural rigidity required to transfer flexural moments. Under this assumption, the base of the bearing assembly is restrained from moving in all directions while allowing small rotations (i.e. pinned support). This is representative of a connection capable of carrying the flexural moments from the cantilever bar by a combination of horizontal and vertical reactions.

Finite Element Results

Stresses and deformations in the yoke and the steel components were obtained as a result of the FE analysis. The deformation of the wood yoke under the bell weight is shown in Figure 7. The maximum vertical displacement predicted by the model at the bottom of the yoke is 0.021 in for saturated wood and 0.016 in for dry material. These values account for the deflection of the cantilever steel bar, which is shown (separately) in Figure . The maximum tip deflection predicted by the FE analysis for the steel bar is 0.013 in. These results confirm that the excessive sagging experienced by the bell is primarily due to the connection failure in the bearing assembly.

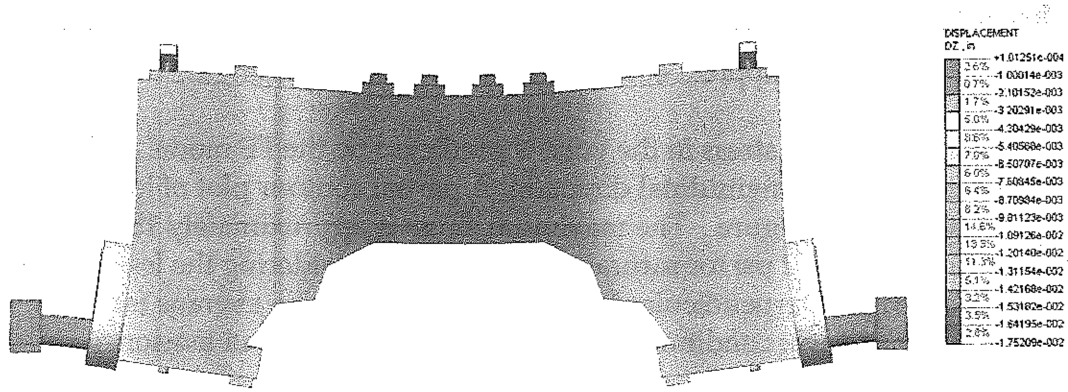


Figure 7. Vertical displacement (Dz) contour plot showing the deformed shape of the support structure under the bell weight.

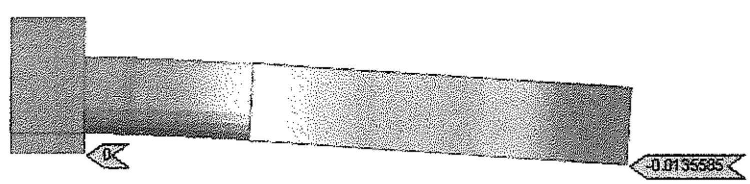


Figure 8. Vertical displacement (Dz) contour plot in cantilever steel bar. Maximum tip deflection of 0.013" was predicted by the FE analysis.

Figure shows the stress distribution in the cantilever steel bar. As the bar bends under the weight of the bell, tension develops in the steel at the top of the axle, which is shown in the figure by the red color. A maximum tensile stress of approximately 6500 psi is predicted by the FE model. When comparing this value to the material strength, defined as the maximum stress that the material can carry without damage and equal to 36,000 psi for steel, a factor of safety of 5.5 is found. The factor of safety is defined as the ratio between the material strength and the applied stress. Based on these results, the cantilever steel bar has enough strength to safely support the bell.

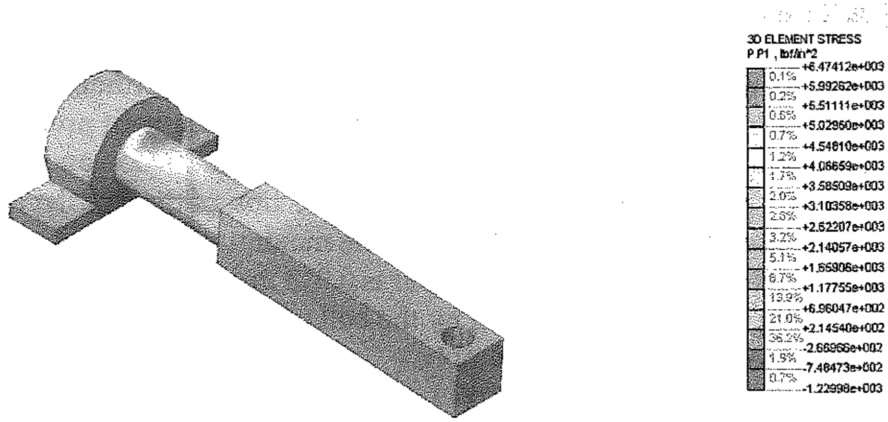


Figure 9. Principle stress (P1) contour plot in cantilever steel bar. Maximum stress (approx. 6500 psi) is below material strength.

The maximum tensile stress in the yoke is predicted by the FE model at the bottom fibers in the longitudinal direction. A partial contour plot of longitudinal stresses is shown in Figure . The maximum stress is approximately 180 psi for dry condition and 172 psi for saturated condition. Considering the lesser value of tensile strength (perpendicular to grain) for the wood, an average factor of safety for dry and wet conditions of 4.5 is found for the yoke in tension.

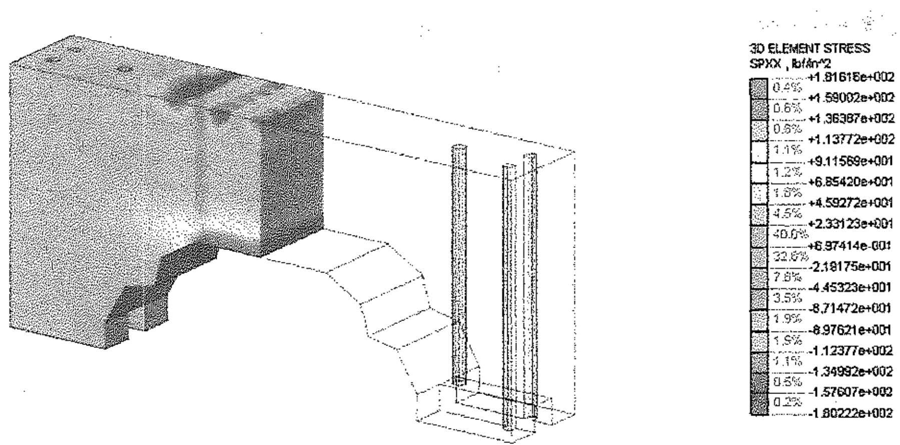


Figure 10. Partial longitudinal stress (Sx) contour plot in yoke (dry condition). Maximum tensile stress at bottom fibers (approx. 180 psi) is below material strength.

The maximum compression stress in the yoke was found at the bearing interface with the cantilever bar, as shown in Figure . Maximum values predicted by the model were equal to 130 psi for dry condition and 105 psi for saturated condition, resulting in factors of safety of 8 and 6 respectively.

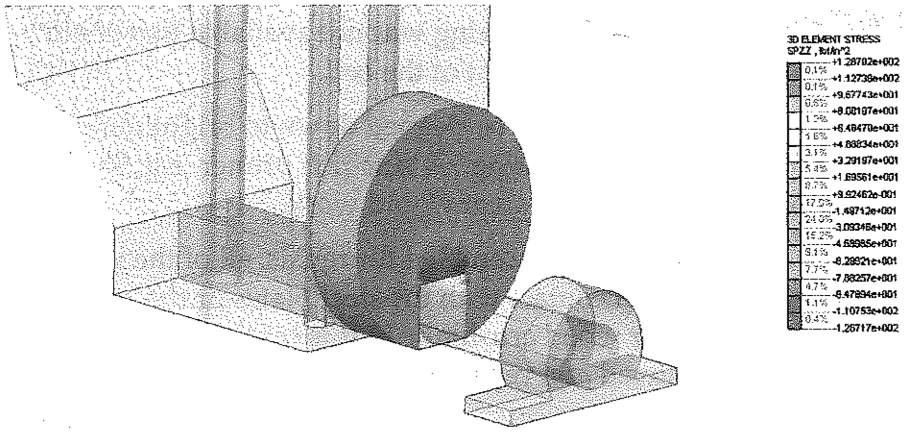


Figure 11. Vertical stress (Sz) contour plot in protruding wood ring (dry condition). Maximum compression stress at bearing interface with cantilever bar (approx. 130 psi) is below material strength.

Summary of the Structural Analysis

A finite element study was conducted to investigate the level of stresses and deformations in the support structure of the Liberty Bell replica. Under the assumption that the base-mounted bearings have the required capacity to prevent the axles from shifting out of alignment, maximum stresses in the wood and steel were consistently found below the corresponding material strengths (i.e. capacity). If the existing bearing assembly, which already failed, is replaced with a new rigid connection, the existing support structure can be retained.

Because of the material deterioration due to weather exposure, actual material properties are likely less than those used in this study. Resistance drilling investigation found that section losses are concentrated at the top of the wooden yoke, where stresses are low. However, because the factors of safety found in this analysis were consistently higher than one by a large margin, it is concluded that the strength of the existing yoke is adequate to support the bell. Based on the results obtained in this study to date, it is considered safe to occasionally ring the bell in a static position, using a rope tied to the clapper. It is not recommended to ring the bell in a dynamic condition, i.e. allowing the bell to swing.

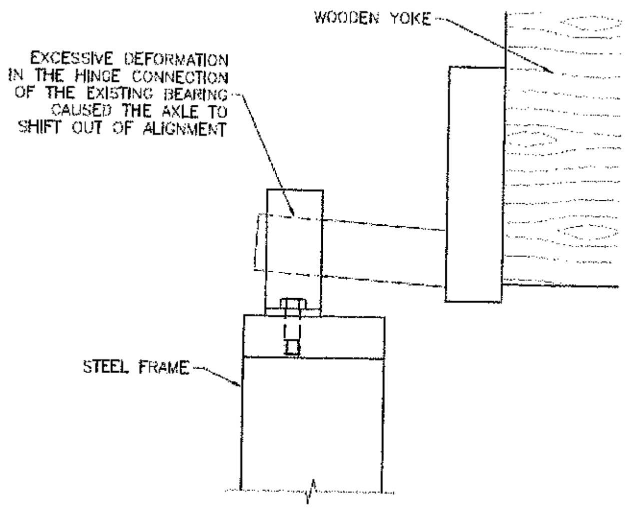
RECCOMENDATIONS

- The existing bearing assembly has failed and must be repaired or replaced (see attached conceptual repair drawing). The bearing assembly should be able to resist flexural moments due to the weight of the bell. This could be achieved by using a wider bearing assembly. Two bearings per side could be used if a single wide bearing was not available that could resist the bending moment due to the weight of the bell.

- Corroded steel elements should be cleaned down to bright metal and protected with appropriate coating. A zinc rich primer, e.g. Sherwin-Williams Corothane 1 or equivalent would work.
- After the support frame is disassembled for repair, all of the wood surfaces hidden from view but in contact with the steel plates or the cantilever bars should be inspected for wood crushing. In this case, the crushed or decayed wood should be removed and repaired using an oak Dutchman repair.
- The weathered surface of the wood can remain as is. Any coating that might be applied would require periodic maintenance and would likely not extend the service life of the wood. If it is desirable to have a fresh look to the wood for aesthetic reasons, it could be sanded and coated with a sealer or stain but this is not recommended.
- The cantilever steel bars are held in place by a set of through bolts. Because of the seasonal volumetric variations in the wood and thermal expansion of the steel, the bolts may become loose over time. Annual inspections of the bolts should be conducted to make sure that the nuts are tight. This will reduce the risk of stress concentrations by providing a more uniform contact between the wood and the cantilever bar.

APPENDIX

Conceptual Repair



1/1 EXISTING CONDITION AT BEARING
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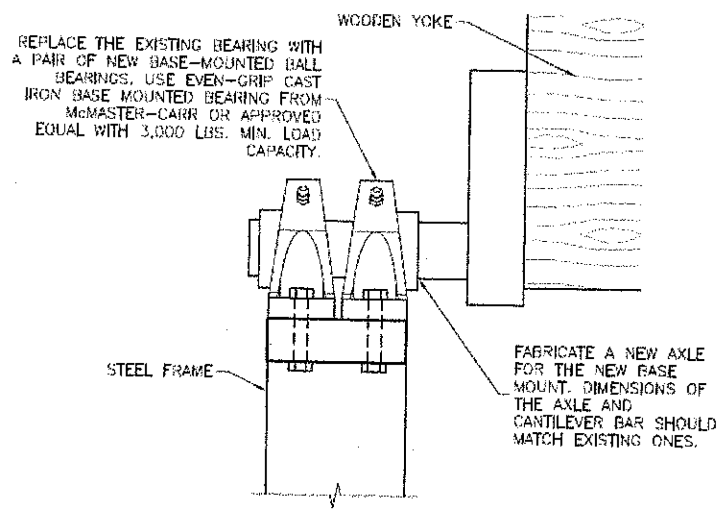

2/1 CONCEPTUAL REPAIR
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Atkinson-Noland & Associates, Inc. Consulting Engineers 2619 Spruce Street Boulder, CO 80302 (303) 444-3620 www.ana-usa.com	DRAWN BY	CAC
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LIBERTY BELL REPLICA
DENVER

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