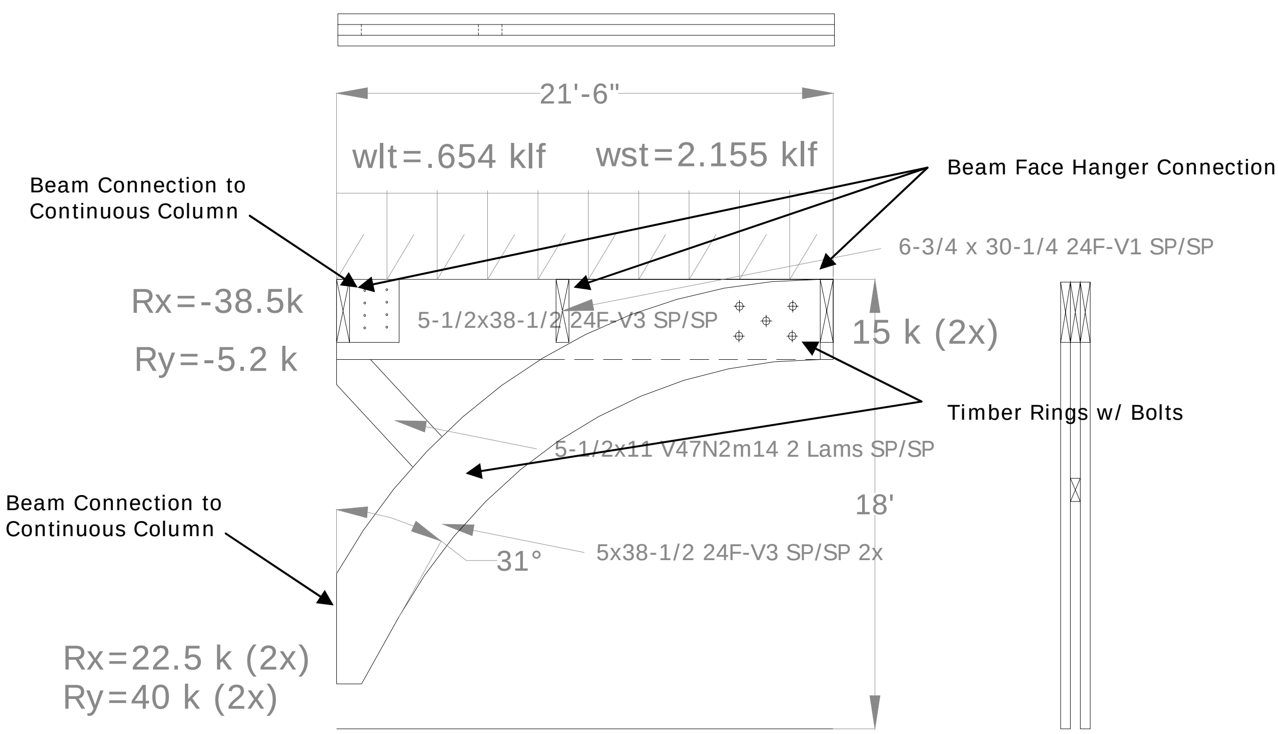
6.0 Structural Design

6.1 Manufacturer

Rigidply Rafters Inc, a manufacturer of glue-laminated timbers and a member of the American Institute of Timber Construction was chosen as the supplier for all of the glued-laminated timbers in this report. *Rigidply Rafters Inc*, is capable of producing glued-laminates up to 14-1/4" wide and supply Southern Pine visual graded 24F-V3 and 24F-V5 's. *Rigidply Rafters Inc*, is located near Lancaster, Pennsylvania, and was chosen for their close approximation for visitations. I was fortune to visit the company on two occasions for their help in compiling the data in this report. A manufacturer closer to Nashville, TN, would be the glued-laminated supplier for this museum.

6.2 Third Floor Cantilever Truss

Fig 6.1 Third Floor Canti-



The third floor has six cantilevered steel girders spaced at 30 ft 0 in with a span of 21 ft 6 in. To design a cantilever member using glued-laminate would not be a viable choice. The required short-term load moment connection for a cantilever necessitating a 100 psf short-term load would be approximately 137 foot-kips which is beyond the capacity of any wood connection and to control the deflection at the free end would require an enormous glued-laminated size beyond the specifications of the NDS as we will see in the fourth floor design.

Alternatives

After several variations, the best alternative design is to use the existing cantilevered member with two curved knee braces on both sides, Fig 6.1 (The methodology was mentioned in the proposal section of this report). The knee braces are curved to allow height clearance from below. This truss is constructed from four components: the cantilevered member (top chord), two curved knee braces, and a kick back brace to prevent the knee brace from "kicking" back. The W40×199 web width (bf) is 15.8 in. Keeping within that width, the total width of the truss must be less than the bf. Therefore the top chord glued-laminated member will be 5-1/8 in thick and the two curved glued-laminates will be 5 in thick, allowing approximately one half inch for connections.

Top Chord

The top chord spans 21 ft 6 in with three equally spaced point loads applied by the joists. The connections between the chord and curved knee braces are analyzed as a pin connection and located at the right end of the chord making the member a simple span beam for straightforwardness. The maximum shear is 30 kips, the maximum moment is 169 foot-kips, and the axial tension is 76 kips. With continuous lateral support on top side beam stability defaults to unity and the positive moment volume factor applies.

Angled Knee Brace (Curved)

Glued-laminates are produced by softening the wood to permit easy bending. The American Institute of Timber Construction, AITC, specification recommends curvature limits. For laminations of 2-in nominal thickness (1-1/2 in actual), the minimum radius of curvature (measured to the inner surface of the lamination) shall not be less than 18 ft 0 in for southern pine lumber. This is the minimum radii, and in no case should the ratio of lamination thickness to inside face radius of curvature, t/R_i, exceed 1/125 for southern pine.

Within the curved glued-laminated knee brace, there are negative moments, shear, and axial compression. The floor to ceiling height below is 18 ft 0 in and coincidently the minimum curvature for a southern pine glued-laminate is 18 ft 0 in. The radius that is used is 21 ft 6 in, the same length as the top chord.

Curvature limit

AITC's specifications limit the minimum radius of curvature, R_i, (measured to the inner surface of the lamination) for southern pine to be no less than 18 ft 0 in. In no case should the ratio of lamination thickness to inside face radius of curvature, t/R_i, exceed 1 /100 for southern pine. When the bending moment is in the direction tending to decrease curvature (increase the radius) the radial stress shall not exceed the allowable radial tension design value perpendicular to grain. If the radial stress is less than 15 psi, then tensile reinforcement is not needed.

When the bending moment is in the direction tending to increase curvature (decrease the radius) the radial stress shall not exceed the allowable compression design value perpendicular to grain.

Analysis

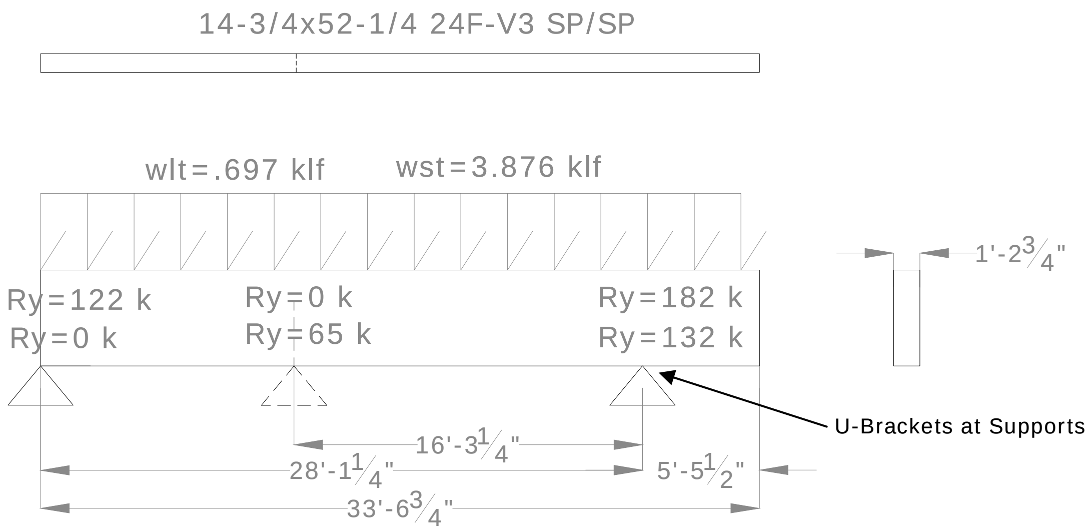
Because the design is hyper-static, the structural analysis was performed in *StaddPro 2002*. All material properties in the software were adjusted for southern lumber. The tributary area is 645 ft^2. Long-term loads of the members are calculated by the software while the long-term loads of the joists were added. Short-term load is 100 psf with a 28 % short-term load reduction based on the ratio of long-term and short-term load. The short-term and joists long-term loads were applied as point loads to the top chord at the connection points. Inputting the loads, the short-term plus creep deflections at the free end of the top chord is 0.792 in, approximately equal to l/D of 326. This deflection limit is slightly less than 360, however this is including creep and judged acceptable. Sizes and grades for the members were governed by deflection and are accordingly in table 6.1. Joists selection were also governed by deflection, and listed in table 6.1. Connections details are covered in the connection section.

Table 6.1 Design Results: Third Floor Cantilever Braced with Curved Knee Braces

Desig-naton	Size	$F_{bxt/t}$ (psi)	$F_{bxc/t}$ (psi)	F_v (psi)	F_c (psi)	F_t (psi)	$F_{c\perp(C)}$ (psi)	E_x (psi)	Camber (in)
Top Chord	5-1/8"×38-½" 24F-V3	2,400	1,950	270	1650	1150	740	1,800,000	
Curved Knee Brace	5"×38-½" 24F-V3	2,400	1,950	270	1650	1150	740	1,800,000	0
Kick Back	5-½"×11" V47N2M14	1400	1600	270	1150 (2 or 3 Lams)	1200	650	1,400,000	0
Joist	6-¾"×30-¼" 24F-V3	2,400	1,950	270	1650	1150	740	1,800,000	0.25

6.2 Third Floor Archive/Library Girders

Fig 6.2 Third Floor Archive/Library Girder



The third floor has six girders spaced at 30 ft 0 in ranging in length from 16 ft to 26 ft with a constant 5 ft 0 in overhang. The structural impediment is the large short term loading required. The girders support the museum's archive and library, requiring a 350 psf short-term load. There were two alternative designs for this particular member. Alternative one was to reduce the spacing to 15 ft. This alternative would require a 12-3/4 × 44 size. Alternative two was to maintain the existing 30 ft spacing and use a larger size, a 14-¼ × 52-¼. Alternative one is 1.5 in narrower and 8.25 in shallower. With a floor to ceiling height of 18 ft 0 in there is adequate clearance for deep members. Alternative one would use twice the members, 12, with a total wood area of 6,732 in^2. Alternative two would use half the number with a total wood area of 4,467 in^2, 33 % less material, so alternative two is judged the best alternative in material savings. In addition, by maintaining the spacing of the girders a 30 ft 0 in, this reduces either the number columns or a transfer girder.

In order to maintain the 30 ft spacing, the width of the glued-laminates exceeded the maximum NDS width of 10.5 in. Size widths are governed by the machinery, particularly the planar. A nearby glued-laminate manufacture, *Rigidply Rafters Inc.*, is cable of producing maximum widths of 14-¼ consisting of a 2"×8" and 2"×6" butt jointed with randomly staggering the joint.

Analysis

The analysis was perform with a mechanics formula. The tributary area is 1,160 ft^2. Long-term loads included the member itself and the joists. Short-term load are 350 psf with a 26 % short-term load reduction based on the ratio of the long-term and short-term loads. The short-term and joists long-term loads were applied as uniformly distributed to the top chord due to the multiple closed spaced joists. Applying the loads, the greatest deflection limit is the short-term load on the overhang with a deflection of 0.18 in, approximately equal to l/Δ of 362 with a limit of 360. Other deflection controls are listed in the table 6.2. Sizes and grade for the member is governed by deflection and is accordingly. Joists selection was also governed by deflection. Connections details are covered in the connection section.

Fire Rating: > 60 minutes

Table 6.2: Design Results: Third Floor Archive/Library Girder

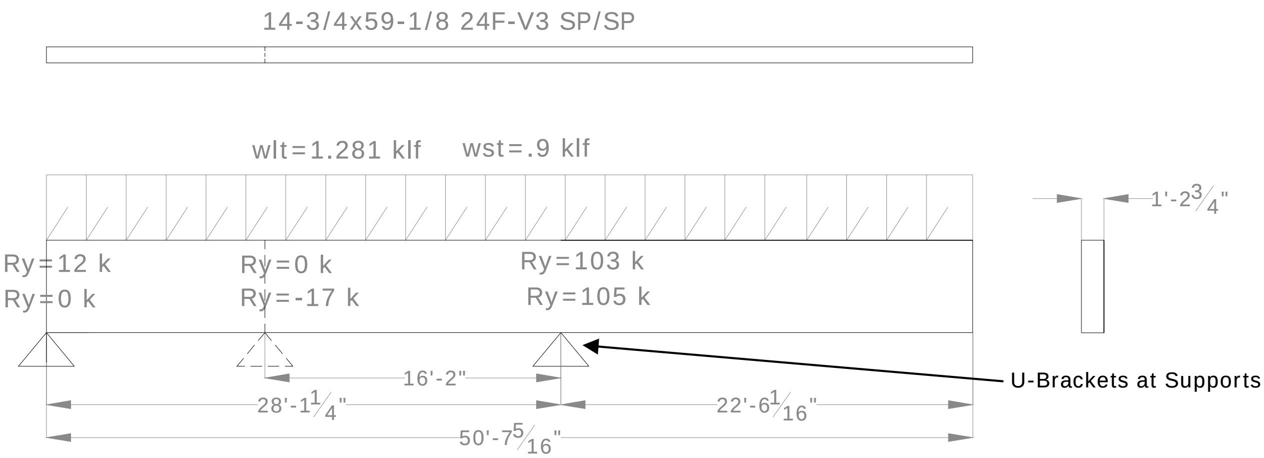
Desig-naton	Size	$F_{bxt/t}$ (psi)	$F_{bxc/t}$ (psi)	F_v (psi)	F_c (psi)	F_t (psi)	$F_{c\perp(C)}$ (psi)	E_x (psi)	Cam-ber (in)
Girders	14-1/4"×52-1/4"	2,400	1,950	270	1650	1150	740	1,800,000	1/16
Joists	6-¾"×30-¼"	2,400	1,950	270	1650	1150	740	1,800,000	1/8

Table 6.3: Deflection Results: Third Floor Archive/Library Girder

Beam			
Δ_{ST}	0.32	$\Delta_{KCR\text{-}LT}+\Delta_{ST}$	0.40
L/Δ_{ST}	1,051 > 360	$L/[(\Delta_{KCR\text{-}LT}+\Delta_{ST}]$	835 > 240
Overhang			
Δ_{ST}	-0.18	$\Delta_{KCR\text{-}LT}+\Delta_{ST}$	-0.23
L/Δ_{ST}	-362 > 360	$L/[(\Delta_{KCR\text{-}LT}+\Delta_{ST}]$	-287 > 240

6.3 Fourth Floor Girders

Fig 6.3 Fourth Floor Girders



The fourth floor has six girders spaced at 30 ft 0 in ranging in length from 16 ft to 26 ft with a constant 22 ft 6 in overhang. The structural impediment is the long overhang seen Fig 6.3. These girders resist the loads from the museum's executive offices and necessitate by code a 50 psf short-term load. There were six alternatives to increase the stiffness of the overhang and control deflection. The first two alternatives are the same for third floor girders in section 6.2. The third alternative is to use knee braces, either straight or curved, to reduce the overhang length. Because of obstacles below, the glass wall and architectural displays, the braces would interfere with the architecture. Alternative four was to experiment with fiber reinforce plastic glued-laminates. As mentioned earlier in the report, FiRPs do not increase stiffness significantly and reasoned unsuitable. Alternative five is to support the overhang with a tension rod to the roof. This would relieve the stress in the member however this does not erase the stresses. The stresses would instead transfer into the roof structure thus increasing their size. Since the girders will be in sight, and appearance is the motive, alternative two is chosen to keep the members spaced at 30 ft and use large size glued-laminates. Thus the required size is 14-¼ x 59-1/8. In addition, by spacing the girders a 30 ft 0 in, this reduces either the number of additional columns or a transfer girder. The sixth alternative, a flitch girder was considered but was overruled in keeping the honesty in the structure.

In order to keep the 30 ft spacing and have stiffness for the overhang, the width of the glued-laminate had to exceed the NDS standard widths of 10.5 in and be sized to 14-3/4 in width. As mentioned previously, size widths are governed by the machinery, particularly the planar. *Rigidply Rafters Inc.* is able to produce a maximum width of 14-¼ by joining a 2"×8" and 2"×6" butt jointed and randomly staggering the joint.

Analysis

The analysis was perform with a mechanics formula. The tributary area is 1,500 ft². Long-term loads included the member itself and the joists. Short-term load are 50 psf with a 40 % short-term load reduction based on the maximum allowed. The short-term and joists long-term loads were applied as uniformly to the top chord because of the multiple closed spaced joists. Applying the loads, the greatest deflection limit is the short-term load and creep on the overhang with a deflection of 0.74 in., approximately equal to l/Δ of 363 with a limit of 360. Other deflection controls are listed in the table 6.4. Sizes and grade for the member is governed by deflection and is accordingly. Joists selection was also governed by deflection. Connections details are covered in the connection section.

Table 6.4 Design Reults: Fourth Floor Girder w/ Overhang

Desig-naton	Size	$F_{bxt/t}$ (psi)	$F_{bxc/t}$ (psi)	F_v (psi)	F_c (psi)	F_t (psi)	$F_{c\perp(C)}$ (psi)	E_x (psi)	Camber (in)
Girders	14-½ × 59-1/8	2,400	1,950	270	1650	1150	740	1,800,000	1/16
Joists	6-¾”×27-½”	2,400	1,950	270	1650	1150	740	1,800,000	1/8

Table 6.5 Deflection Results: Fourth Floor Girder w/ Overhang

Beam			
Δ_{ST}	0.0	$\Delta_{KCR\text{-}LT}+\Delta_{ST}$	-0.02
L/Δ_{ST}	-68,602	$L/[(\Delta_{KCR\text{-}LT}+\Delta_{ST}]$	-21,003 > 360
Overhang			
Δ_{ST}	0.23	$\Delta_{KCR\text{-}LT}+\Delta_{ST}$	0.74
L/Δ_{ST}	1187 > 480	$L/[(\Delta_{KCR\text{-}LT}+\Delta_{ST}]$	363 > 360

6.4 Roof Trusses

There are six W40×199 columns at the rear of the building. To employ their full capacity they will be used to support the glued-laminated roof trusses which will frame the 2-1/2 : 12 mono-sloped roof (*Fig 6.4*). The two illustrated trusses are located on column lines J8 & J, respectively, in respect to the structural plans in Appendix A. Truss J is truncated due to the middle rear of the building having an inset. The six W40×199 columns are spaced at 30 ft thus spacing the truss at 30 ft. There will be nine truss, seven which will be truncated. The truss members sizes for J & J8 are 24F-V3 southern pine 8-1/2" × 23-3/8" and 10-1/2" × 23-3/8" respectively. The truss design is a Warren truss with the diagonal webs positioned in a defined way to carry compression only. The archetype designs had webs compressed and tensed. The tensed webs were tensed upwards to 400 k. A typical shear plate can resist approximately 5 kips, thus 80 shear plates would be needed which is implausible. With all the webs compressed, as illustrated in *Fig 6.4*, the greatest compressed force is 300 k which is within the bearing capacity of the webs at 500 k. Perpendicular compression for the bottom and top chord by the webs is another concern. The webs connect into the bottom and top chords, bearing at an angle to grain. The bearing stress is somewhere between parallel and perpendicular compression and is determined by *Hankinson Formula*. The bearing angle capacity is greater than the compressive forces that are exerted by the webs to the top and bottom cords and ruled satisfactory.

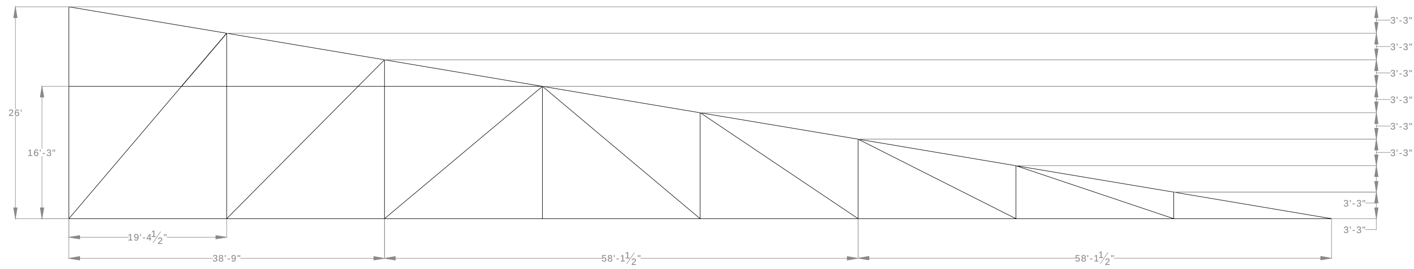
Transporting this trusses to site is another issue. The truss are to large to truck on to site and would very time consuming to assemble on site. Figure 6.5 illustrates how the truss will be shipped to minimize costs. Length wise, the top and bottom chords would be built with continuous members, up to lengths of 60 ft, allowing up to three bays to be fully assembled. Height wise, the truss is segment in the middle. The top pieces are known as cap trusses. A typical tractor trailer is 53 ft long and special arrangements and designated routes can be devised to bring these trusses on site by truck.

The purlins will be spaced eight feet on center and specified as 24F-V3 6-3/4x27-1/2 SP/SP.

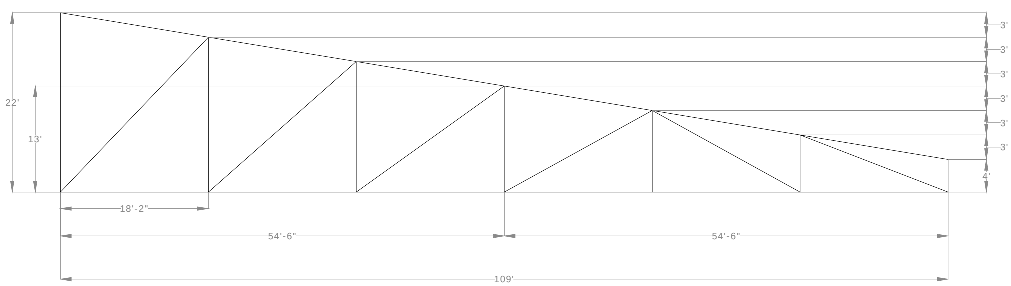
6.5 F.I.R.P.

Fiberglass Reinforced Plastic (FIRP) glued-laminates are manufactured with one or more thin layers of a fiber reinforced panel. The reinforcing consists of high-strength fibers embedded in a matrix and are strategitically placed between certain laminaotions to increase beam strength and stiffness. Three types of reinforcing are currently approved for use in FIRP beams: Aramid, Carbon, and Fiberglass. After running through several calculations the reinforced plastics increase moment

Fig 6.4 Mono-Sloped Trusses J-8 & J



Truss Located at Column Line B & J.8 C



Truss Located at Column Line D, E, F, G, J, & H

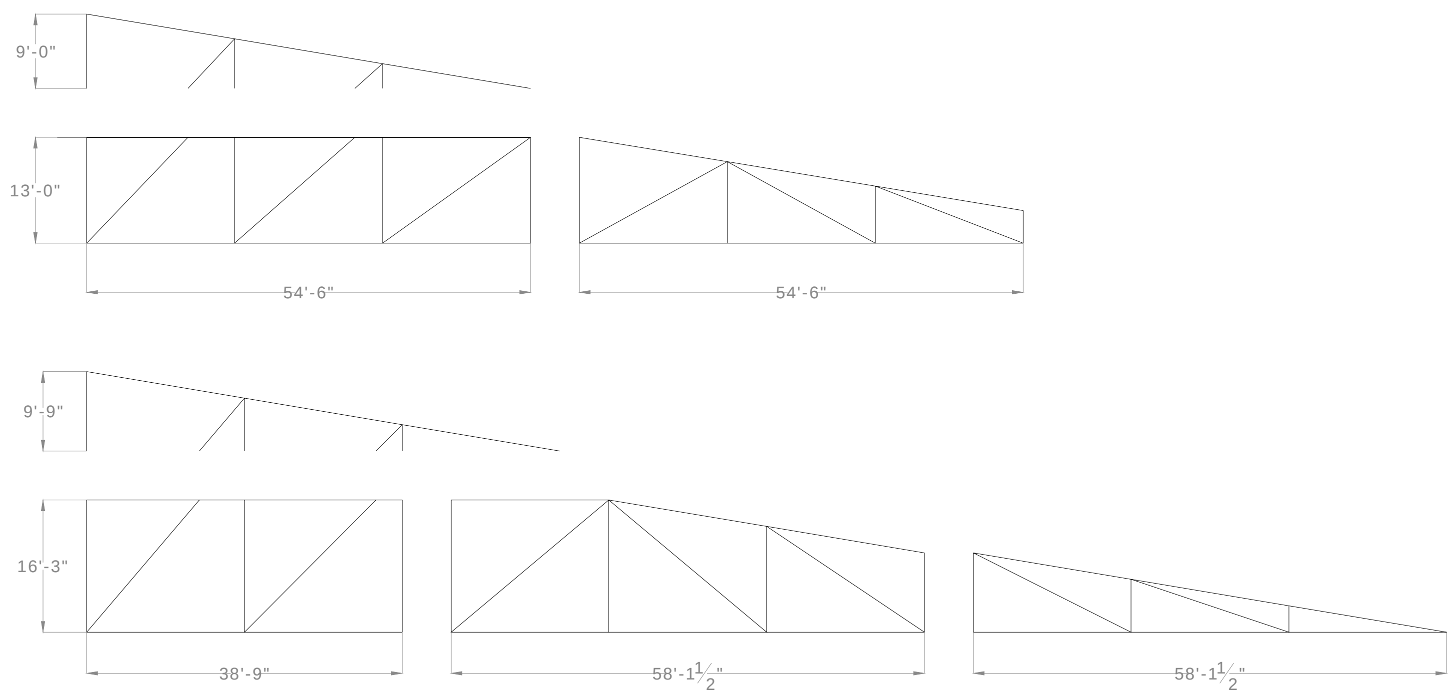


Fig 6.5 Mono-Sloped Trusses J-8 & J—Segmented for Shipment

capacity but do not increase stiffness significantly. All of the designs are controlled by deflection and FIRPS increase stiffness by only 10 %.

6.6 Columns

The columns that will support the glued-laminate floor can be either steel columns enfolded in wood veneer or glued-laminated columns. Steel columns are favored for their high strength capacity but in keeping with the honesty of the structure, glue laminated columns will be used on the second and third floor (there are no columns on the fourth floor). To verify if a glued-laminated column is adequate to carry the heaviest axial loads from a girder reaction, the largest vertical load is located underneath the third floor archive/library supporting the third and fourth floor. The size required is a SP V49 N1M16 4 LAMS 12-3/4" x 12-3/4" (V is visually graded; 49 is the combination number, N1 is number one grade lumber, M is medium density grain, and 16 is the slope of grain, in which it can not exceed 1 : 16). This size can be assembled using a 2x8 and 2x6 edged butted (The depth of a 2x12 is only 11-1/4). The prominent disparity between glued-laminated columns and beams is the edge gluing required for the columns. Edge gluing the columns controls lateral buckling. Knowing a 12-3/4 x 12-3/4 is capable of supporting the 3rd floor archive/library and fourth floor office spaces, all other columns will be ample for glued-laminates.

6.7 Hall of Fame Roof

Part of the proposal was to redesign the Hall of Fame's stair-stepped roof with either exposed sawn lumber or glued-laminated timbers. At the time of the proposal it was unaware that the entire roof structure was a rigid frame with a compression ring at the top most roof. Knee braces or a complete redesign with joints would be the only solution, and with the additional weight of an ornamental radio tower at the center, the frame has been decided to leave as is.

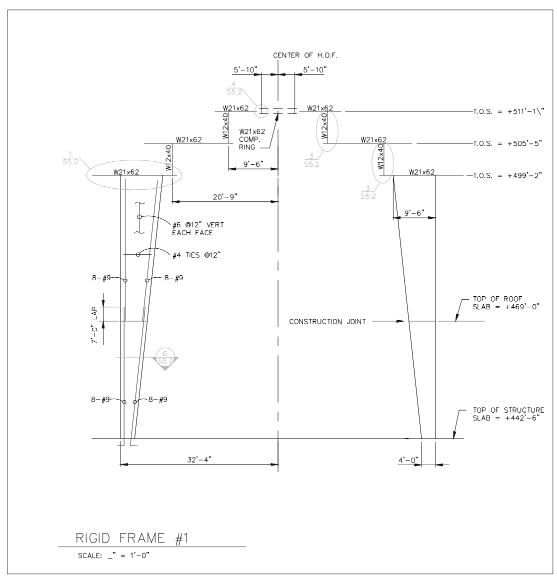


Fig 6.6 Hall of Fame Stair Steep Roof