Computer-Aided-Design of Concert Staging

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ABSTRACT

Concert stages contain many complex geometries and structural components, making their design a difficult task. Equally difficult is the assembly of a concert stage, since proper construction of it's various components is vital to ensure structural integrity. Computer-Aided-Design (CAD) is a necessary tool in staging design and analysis. CAD can be used to show the overall structure of the stage, break the stage down into its various constituent components, and show how the individual stage members are connected. Using solid modeling, the solid representations of the components and individual members assist in visualizing the complex components and their interconnection. CAD techniques are essential in envisioning how various members of the stage fit together, and to show the step-by-step process of stage construction. Also, the use of the CAD model is invaluable in any structural analysis. After translating the CAD model into an IGES file, the structure can be imported into a finite-element program, which can then be used to evaluate the integrity of the stage by examining existing stresses.

Introduction

Concert stages are very intricate in design. The stage discussed in this paper contains over 20,000 members, each of which plays a vital role in the support and stability of the structure (BOCA, 1993) (Johnston et al., 1986). Due to this intricacy, it is essential to know how each of the various components and members of the stage fit together, thus completing the structure. Computer-aided-design is an integral part of both the design and analysis of the stage. Isometric stick figure drawings of the entire structure are produced using CAD, with each row and column of the structure arranged on separate layers to facilitate further analysis. Solid models of various components of the stage aid in visualizing the connections of individual members. Both the stick figure layouts and solid models are produced using CAD software, and aid in demonstrating how the structure is assembled.

The main focus of the work discussed in this paper is a full structural analysis of the entire stage structure. All of the elements in the stage were generated using the computer-aided design software CADKEY; solid models were generated using SilverScreen. The CAD model of the stage was imported into the finite-element analysis program ANSYS, using an IGES translator. The entire structural analysis performed in the project was dependent upon the accuracy of the CAD drawings. Any errors present in the computer-aided rendering of the concert stage would have caused error in the analysis of the structure.

The final step in the completion of this project was the compilation of a stage design manual. This manual contains both CAD line drawings in two and three dimensions and the solid modeling information describing the basic design and construction of the stage. In addition, the design manual contains descriptions of the stage loading and theoretical information which is used in the analysis. Since the stage is actually a temporary structure, municipalities in which the stage is to be erected must issue building permits prior to construction. The design manual is presented to the municipalities as validation of the design and structural integrity of the stage as laid out in the appropriate building codes (BOCA,1993), thus facilitating the issuance of the permit. Therefore, the CAD work is an integral part in both analyzing the structure and providing a way for others to examine the results of such an analysis.

Background

This work is the product of a grant which was obtained from Mountain Productions, a designer of staging products located in northeastern Pennsylvania. As a result of the heavy liability burden on the company, the concept of stage analysis was born. The outcome of the grant was a complete structural analysis of two stage designs; the differences being the size of the roof and applied loads. The analysis results, various building and analysis techniques, loading, and background materials were compiled into book form and presented to municipalities to assist in obtaining building permits for these temporary structures. The stage presented in this work is erected, during the summer months, in three locations; Scranton, PA, Harrisburg, PA, and Jones Beach, NY. Over the past fifteen years, this stage type has been employed by numerous rock bands, i.e. Aerosmith, Bryan Adams, Van Halen, and Boston, to name a few.

CAD and Solid Modeling

This paper is a detailed presentation of stage design using CAD techniques. The general process of designing a large-scale concert stage will be presented. The stage design considered can be divided into three major components, as shown in *Figure 1*; roof truss, sound wings, and stage floor.

The roof truss structure, shown in various views in *Figure 2*, is the first major component of the stage to be assembled. The truss is 49 feet up-stage, 70 feet cross-stage, and consists of approximately 2,000 aluminum

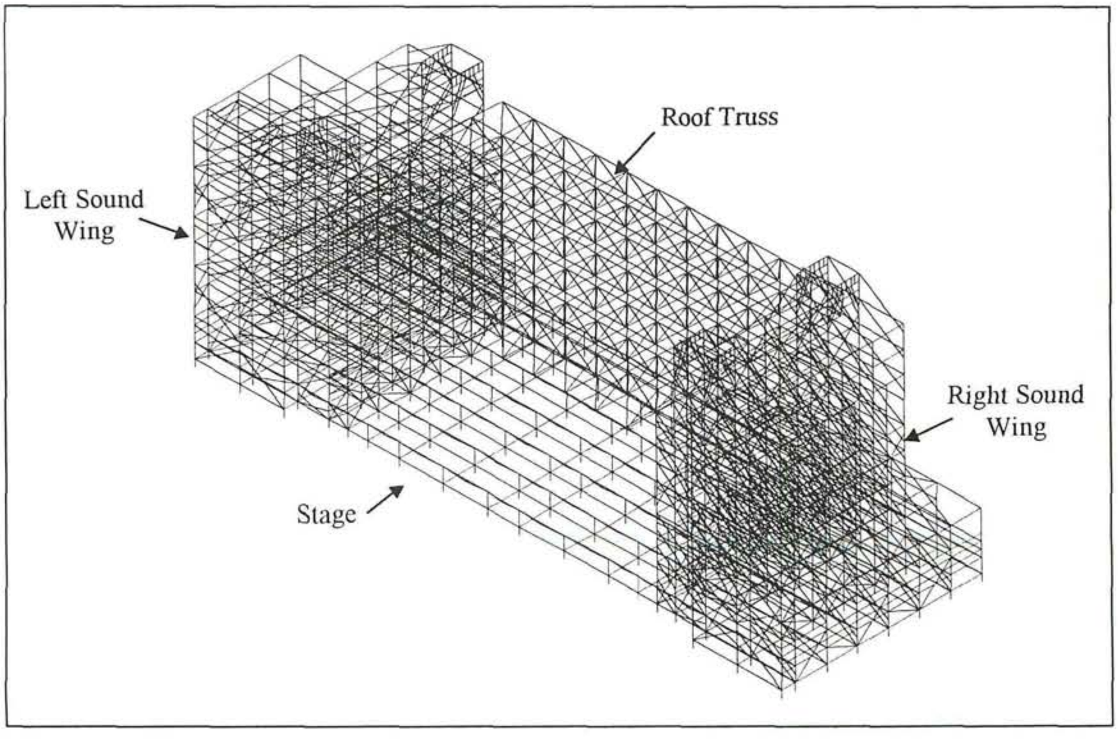

Figure 1 - *CAD representation of stage design.*

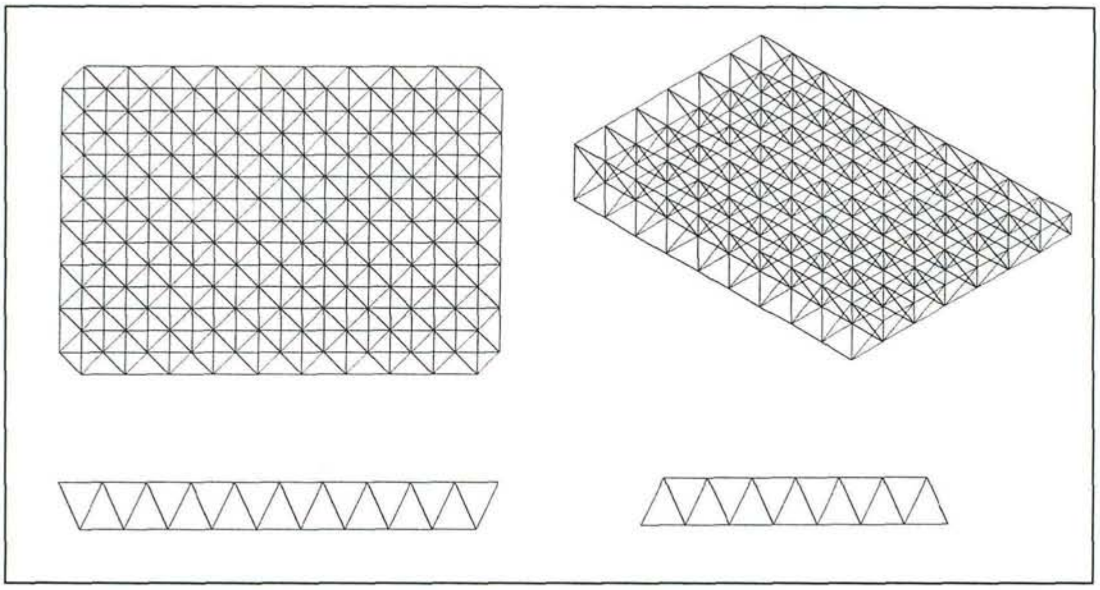

Figure 2 *- Roof truss - isometric, top, front and right-side views.*

members with a total material weight of nearly 9,000 pounds. CAD was used to draw the roof structure as line elements as shown in *Figure* 2. To an individual unfamiliar with the roof truss structure, such as a municipal engineer who must issue a building permit, solid modeling is used to demonstrate the complex connection scheme for the roof. *Figure 3* shows a solid representation of one of the roof members. The roof is comprised of members of similar cross-sections and differing in lengths; the horizontal and vertical members shown in the top view of the roof (*Figure 2*) are 7 feet in length, and the diagonal members are 10 feet in length. Upon closer examination of the roof member solid model, it can be seen that aluminum end pieces, or slugs, are present of both ends of the member. These slugs are welded to the ends of each member and 3/4-inch diameter holes are drilled; these holes are used for connection purposes, as will be shown.

Mending plates (*Figure 4*) are used to connect the structural members of the roof. Each

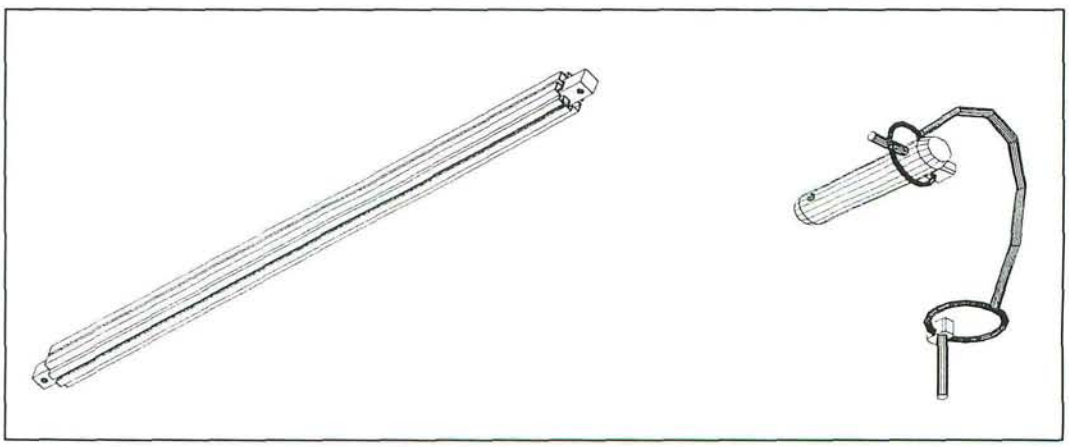

Figure 3 *- Solid model of roof member and locking pin.*

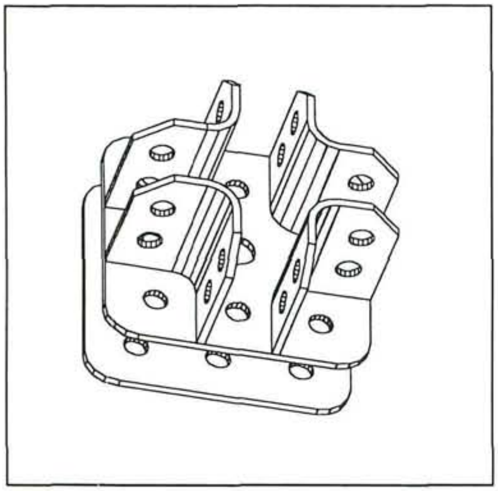

***Figure 4**- Solid model of mending plate.*

plate has a number of holes drilled into it, allowing for the connection of horizontal, vertical, and diagonal roof truss members. The holes of the mending plate are the same diameter as those drilled into the end pieces (or slugs) of each roof truss member. Locking pins (*Figure 3*) are used to secure members to the mending plate.

To detail the assembly process in the design manual, solid modeling is used to show exactly how these roof components are connected thus creating the roof structure. *Figure 5* shows that the roof member positioned such that the hole in the slug and the hole of the mending plate are aligned. Next, a locking pin is inserted through the two holes, attaching the member to the plate. Finally, the safety rings are attached to the pin and snapped into the locked position, assuring a secure connection. This process is repeated for each pyramidal section until the entire roof truss is assembled.

After the roof truss is assembled, the side sound wings of the stage are constructed. The left and right sound wings are symmetrical to each other; for this reason, only one needs to be visualized. The sound wings are the sole support mechanism for the roof truss, which weighs approximately 21,300 pounds (including both the material weight of the roof truss and the weight of the equipment which it supports). Due to the necessity of supporting these extremely high loads, the side sound wings are the most complex and crucial of the stage's major components. Each sound wing consists of approximately 4,000 steel members, most of which are 1.9 inch in the outer diameter and 1/8 inch wall thickness. *Figure 6* shows a line element CAD representation of the stage's right sound wing.

The first step in the assembly of the sound wing is the erection of its vertical members (standards) in a 7 foot by 7 foot or 7 foot by 10 foot box pattern. Once the vertical standards are erected, they are interconnected

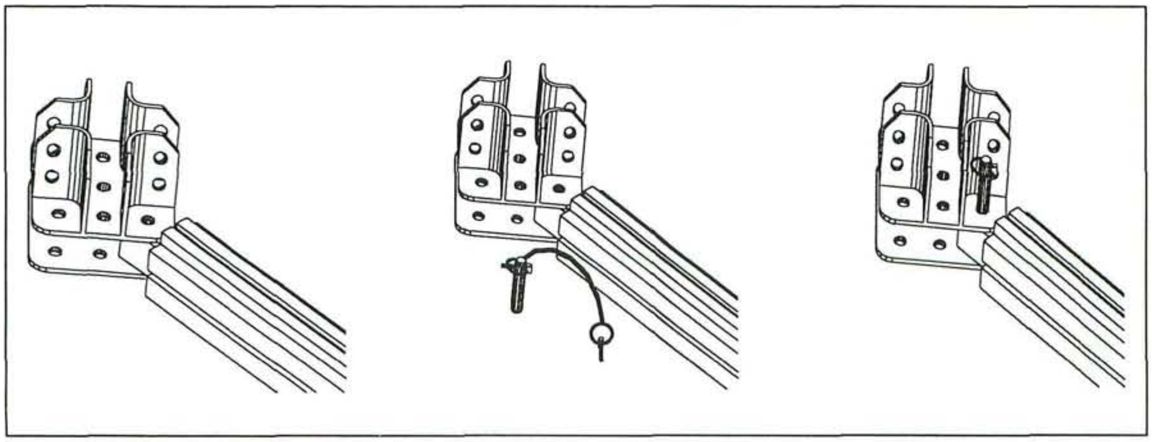

***Figure 5** - Connection of roof member to mending plate.*

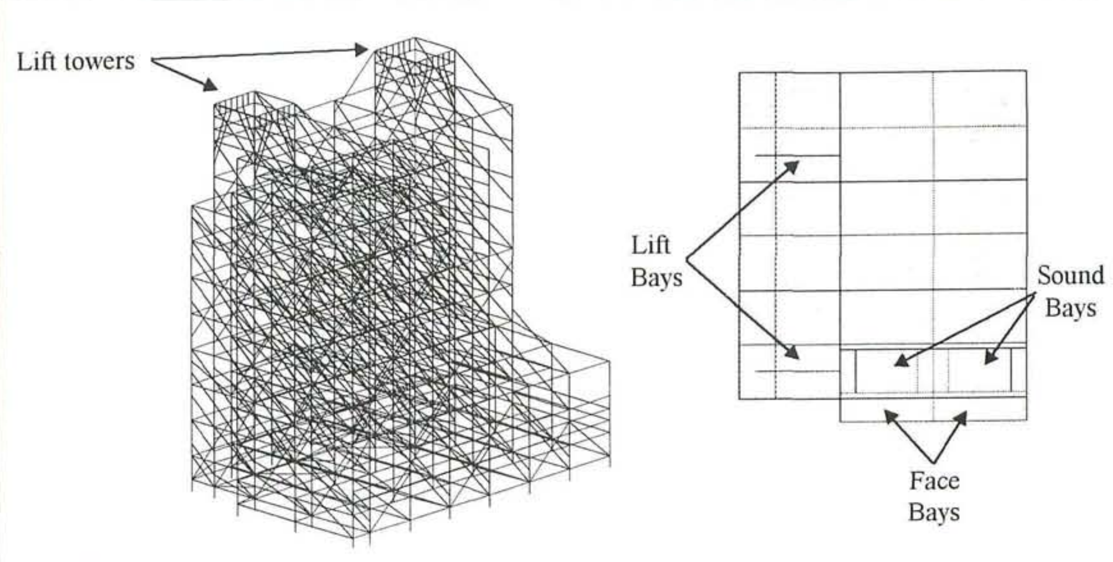

Figure 6 - *CAD representation of right sound wing (shown in isometric and top view).*

with bracing members which provide added support to the structure. Rosette plates, shown in *Figure 7*, are present at .5 meter intervals along each of the vertical standards. These plates are used to connect the bracing members of the sound wing; as seen in *Figure 7*, each rosette plate has eight cut-outs for the connection of bracing members.

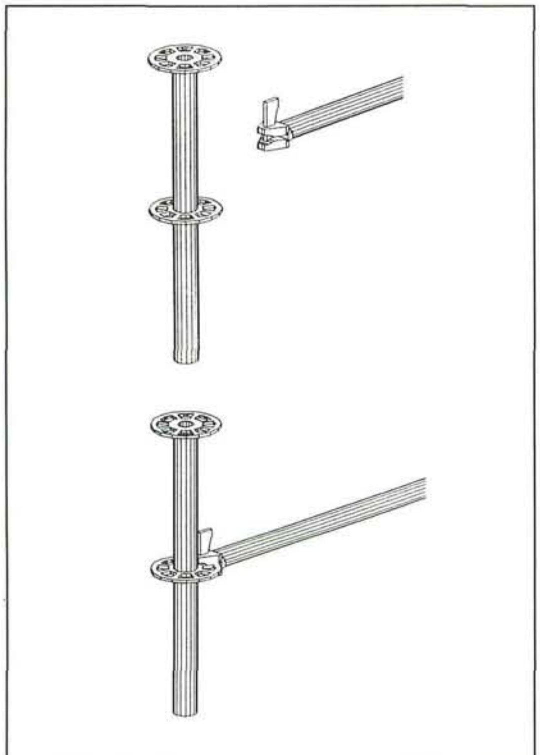

Figure 7 - *Connection of a bracing member to a rosette plate.*

Each bracing member has captivated locking levers at the ends and are used to connect and properly secure the bracing members to the rosette plate, as shown in *Figure 7*. Basically, the member is placed such that the captivated locking lever is positioned around the proper cut-out of the rosette. Then, the lever is inserted into the cut-out and tapped into place with a rubber mallet to properly secure the connection.

Each sound wing, as seen in *Figure 6*, is divided into bays which vary in both height and width. The lift bays are used to raise the roof into place, the sound bays provide support for the sound equipment. In order to facilitate the finite element analysis of the complete 3-D structure, each row and column of the sound wing was drawn on a separate level; a total of 25 levels were used for the complete sound wing model.

When both the right and left side sound wings are fully assembled, the roof is rigid-

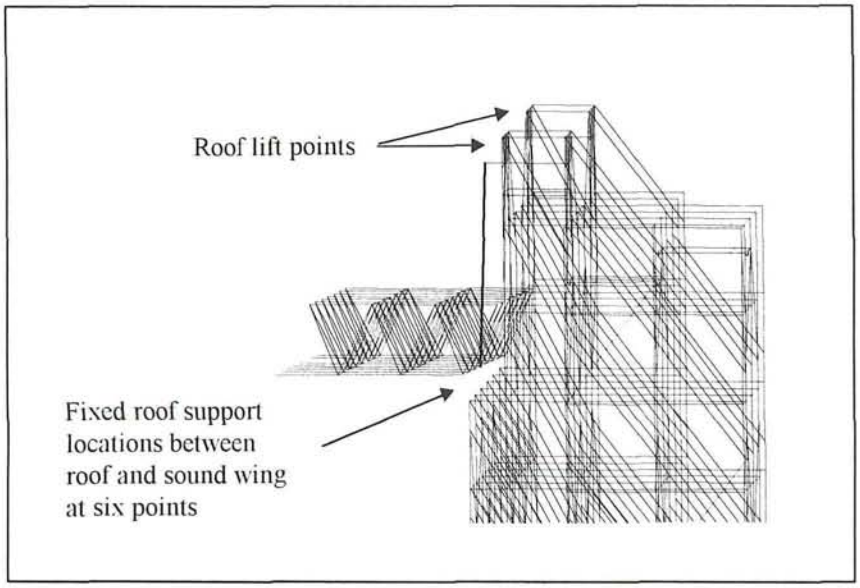

Figure 8 *- Attachment of roof truss to sound wing.*

vertical with six 1/2 inch steel bolts (shown in *Figure 9)*, then the upper portion is connected using four 1/2 inch steel bolts. Once the compression block has been fully mated, the mending plate of the roof truss is connected using a 3/4 inch steel bolt, as seen in *Figure 9*. This procedure is repeated until the roof truss is properly secured at each of the six points on each sound wing; the tension in the steel cables is then removed from the roof and lift towers, and the roof truss is solely supported by the sound wings.

ly attached to the inner-most bay of each sound wing. The lift towers (*Figure 6*) are used to raise the roof into position using 5/8 inch steel cables, hung from each tower. Once the roof truss is raised into position, it connected to the vertical standards at six points, shown in *Figure 8*, on each side using a compression block. First, both sides of the lower part of the compression block are connected to each other enclosing the

The last major component of the stage to be assembled is the actual stage truss system and floor. The stage is comprised of a simple framing system and wooden decking which is available in two sizes: 3.5 feet x 7 feet and

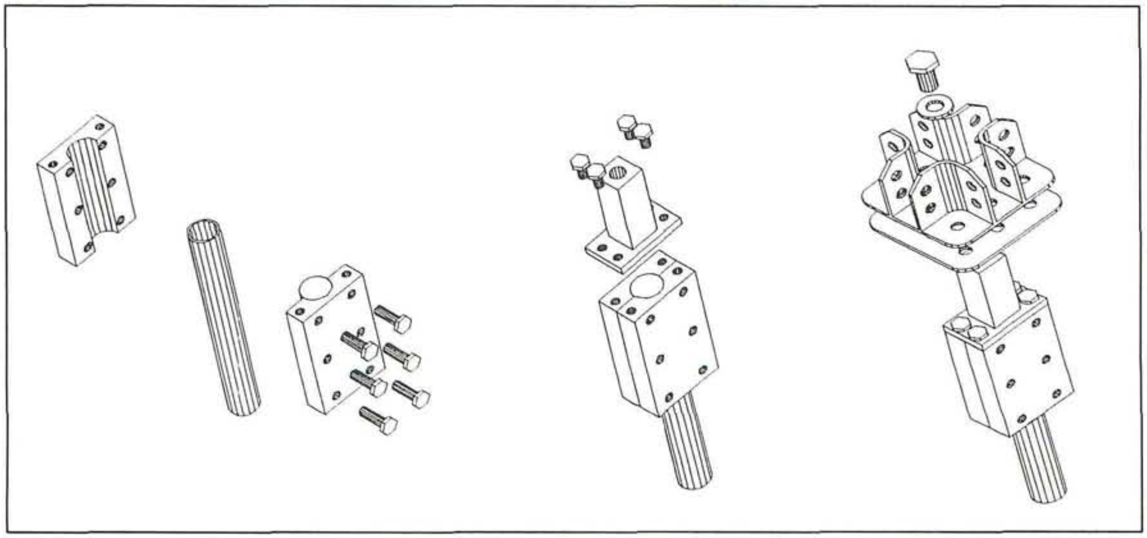

Figure 9 *- Compression block assembly.*

3 feet x 7 feet. Each piece of decking is reinforced with wooden and aluminum ribbing on its underside (*Figure 10*), thus increasing the flexural rigidity of the floor, up to 125 pounds per square foot. The stage framing system is constructed using steel bracing members, gussets, and the rosette plates attached to the vertical standards; using these components, the grids of the framing system are constructed. Once the stage floor framing is completed, the pieces of decking are lowered into position, snapped into place, and locked into the frame (*Figure 11*).

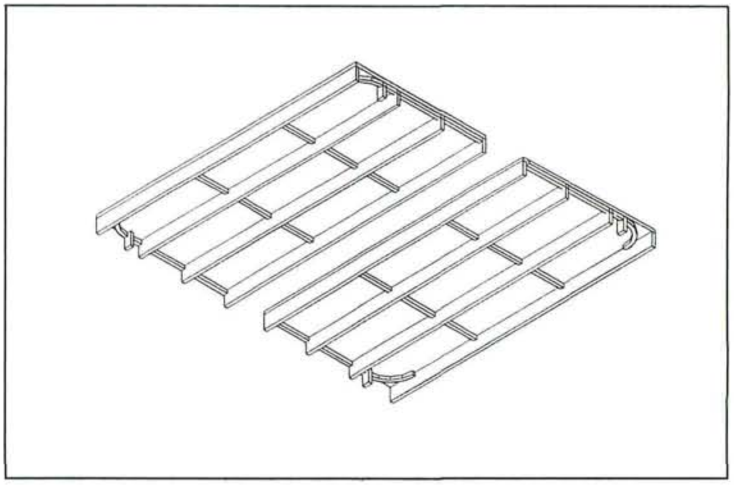

Figure 10 *- Underside of stage floor decking - 3.5 foot x 7 feet decks.*

The framing system is divided into grids which are 7 feet x 7 feet and 7 feet x 10 feet, each section of the stage frame will accommodate either two or three pieces of decking placed flush against one another.

The last components of the stage to be added are the rain and wind tarps (*Figure 12*), which protect the sound and lighting equipment (and the performers) in the event of inclement weather. These tarps can be removed to reduce the dynamic loading acting upon the structure when wind conditions exceed a specified velocity (50 mph). Under wind conditions, the tarps act as wind barriers, thus, transmitting large forces to the structure. At wind levels above 50 mph, the external tarps are removed; the resulting surface area on which the wind acts is then minimized.

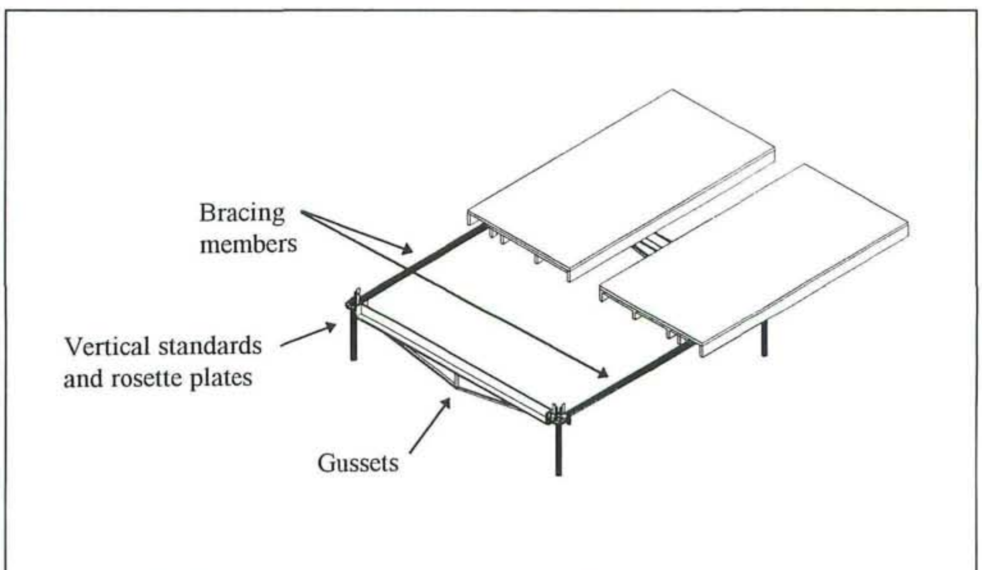

Figure 11 *- Stage deck placement for 7 x 7 foot grid using two 3.5 x 7 foot decks.*

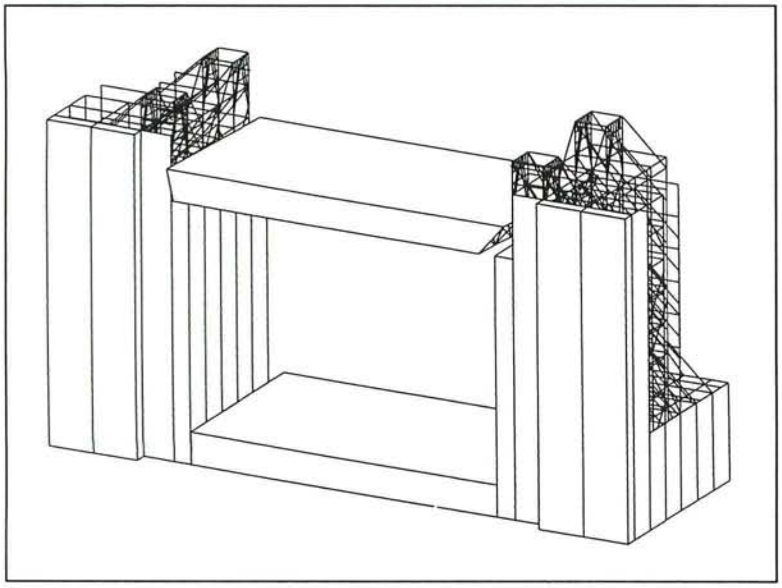

Figure 12 - Concert stage shown with protective tarps in place.

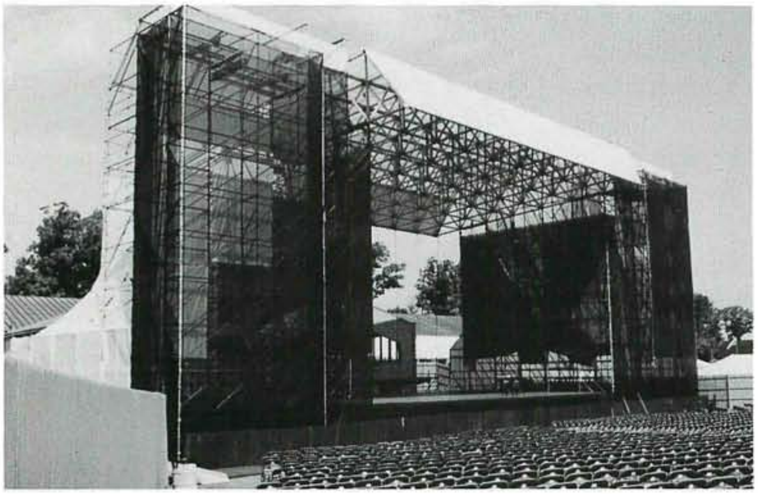

Figure 13 - Placement of actual stage.

Analysis

The main focus of the project discussed in this paper was a full structural analysis of the complete stage, to determine the integrity. To fully analyze the structure, each member had to be examined to ensure that allowable axial, bending, and buckling stress values were not exceeded (Shigley and Mischke,1989) (Beer and Johnston, 1992). CAD was a useful and very powerful tool in accomplishing this task. For the analysis portion of the project, Finite-element analysis (FEA) was utilized. FEA uses the geometry of the structure, along with the cross-sectional properties of the members, in addition to applied loads and constraints, to determine the various stress values (Cook, 1995). In this analysis, it is very important that one know the exact locations where elements connect; this was easy using CAD.

The CAD files produced during the course of the project were used to accomplish two tasks in the area of FEA. First, the CAD drawing shown in Figure 1 was translated into an IGES format and then imported into finite-element software, thus, the geometry was used for the FEA model. Also, the CAD print-outs of the members were labeled with all of the link connection information; i.e. nodes and elements. In addition to the complete stage model which was constructed as a stick figure, analysis was performed on solid models. In this case, IGES formats of component CAD drawings were imported. Two- and Three-dimensional models of the drawings were created and analyzed; the stress patterns for the rosette plate are shown in *Figure 14*. Thus, the CAD work done throughout the course of this project was useful not only in describing assembly procedures, but also in simplifying the complex analysis performed on the stage.

Conclusion

This paper demonstrates the many uses of CAD in the design and construction of a performance stage. CAD can be used to envision the complex connections within the structure and to show how the stage is properly assembled. There are many applications for the computer-aided-design work presented in this paper. During the past years, municipalities have become more rigorous in their inspection of mobile staging. The stage must gain the approval of the municipality before a building permit is issued and assembly can begin. For this reason, an engineering data manual was compiled to present the stage's construction and structural integrity validation to such authorities. CAD renderings are referred to throughout this manual to give a visual overview of how the stage is assembled. CAD is also heavily related to the analysis of the stage. The CAD drawings are imported into the finite-element analysis package, ANSYS, thus saving time in modeling the complex structure. The analysis performed can be used to determine different stresses present in the various members of the stage, which consequently give factors of safety for each member. In this respect, the CAD work done in the early stages of an analysis project such as this is constantly being utilized. Both CAD and solid model representations provide an essential reference not only for the design and assembly of a concert stage, but also for the analysis of the structure.

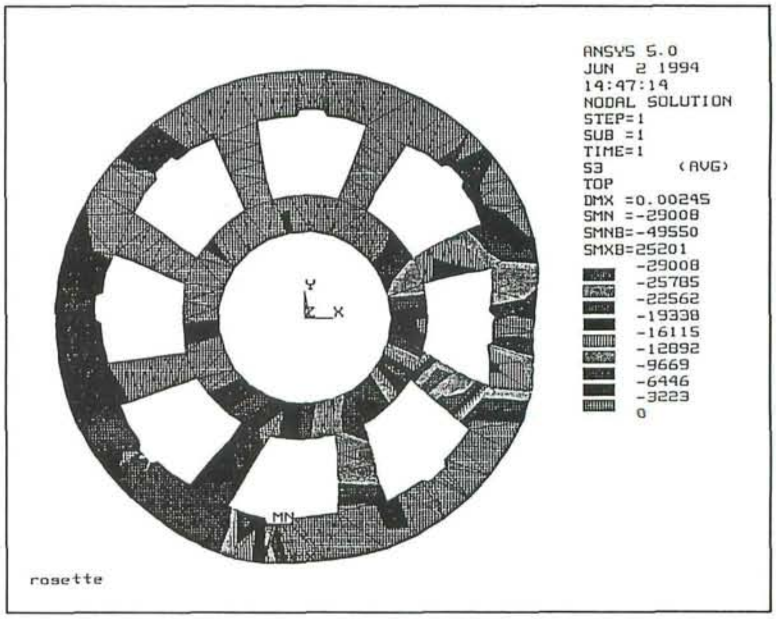

Figure 14 - *Stress pattern from a loaded rosette plate.*

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