HEAVY MOVABLE STRUCTURES, INC.

NINTH BIENNIAL SYMPOSIUM

"Preserving Traditional Values with New Technologies"

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ADVANCES IN THE DESIGN OF COUPLED MECHANICAL-STRUCTURAL SYSTEMS

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MACHINERY/MECHANISMS

Introduction

Mechanical systems are difficult to design and analyze. Load conditions are complex and variable, making it difficult for the designer to review every possible scenario. Boundary conditions are inherently difficult to quantify and subject to significant engineering judgment. Each system is a prototype, making the risk of initial performance problems significant and the cost of modifications or repairs to correct these problems high. Even more costly consequences of design mistakes are high maintenance costs, system downtime (loss of service) and shortened service life, all of which increase the lifecycle cost to the operator of the system.

This paper proposes a fundamental shift in the way we as an industry approach the design of coupled mechanical-structural systems. This new approach is aimed at improving the quality of the designs, eliminating surprises that show up during system commissioning and reducing the total lifecycle costs to the system owner. This new approach is based on three new technologies:

- **3D Parametric Modeling** Software – used to improve the definition of the design, reduce errors and omissions, improve overall coordination, and aid in communication of design ideas.
- **Advanced Finite Element Analysis** Tools – used to better understand how mechanical elements such as bearings interact with the structural system.
- **3D Kinematic/Dynamic Modeling** Software – used to develop "virtual prototypes" of the moving system to improve the designer's understanding of the interaction of the mechanical components and control system with the moving structure.

This approach has been used in the aerospace and automotive industry resulting in tremendous reductions in change, errors and rework. By carefully adopting proven tools from these industries, and adapting them to the unique design challenges inherent in our industry, we can drastically improve the performance, usability and dependability of heavy movable structures. As always, the use of new technology does not eliminate the need for competent engineering judgment, but instead supplements it with additional information and therefore results in faster, higher quality designs.

3D Parametric Solid Modeling

Current Practices

One of the fundamental skills required of an engineering practitioner is the ability to generate creative solutions to a problem and to communicate those solutions to others. Because of the limitations of written language, drawings and diagrams have long been an essential tool used by engineers to communicate their ideas. The art of communicating through technical drawings has gradually developed from the elegant sketches used by early engineers such as Leonardo daVinci to the more precise standards-based engineering drawings used today.

In the early 1980's, the wide adoption of 2D computer aided design (CAD) software brought a significant change in the way engineering drawings are developed. The software made it much easier to copy and revise drawing data and has greatly improved the development of engineering documents. Unfortunately, this migration to 2D CAD based drawings had other unintended consequences. The ease of copying geometry and views has generally led to more drawing sheets being used and therefore more data to check and more opportunities for mistakes and ambiguity in the design documents.

Another more serious consequence has been reduced reliance on a "master layout drawing" developed and maintained by a key design engineer. These drawings have traditionally been the master source of all geometry for a design and relied heavily on idealized datums (elevations, column numbers, top of floor, top of steel, etc.) to define the relationship of the design to the overall project. A small number of thoughtfully selected detail views and sections were then developed from this master layout to show specific details of the design. Each section or view was carefully constructed to show only the desired details and to index those details back to the datums. Current drawing practice tends to develop new details by copying existing details rather than starting with the master model. These details tend to show more geometry than is absolutely needed and often the relationships to the critical datums are omitted since they are not required to develop the view. Because new details can be created very quickly, less thought goes into determining the minimum number of detail views required to communicate the design intent. Drawing sets tend to get larger and more cumbersome to keep coordinated. Any original errors in the copied views get propagated from sheet to sheet.

While these trends in drawing development affect both structural and machinery drawings, they are far more problematic for the machinery designer. With structural drawings the engineer can expect skilled detailers to transform the engineering documents into detailed fabrication drawings based on rules and standards established by engineering specialty organizations such as AISC. For operating machinery, the variety of machinery types and the small number of installations has not allowed for the development of a similar network of skilled detailers and all-encompassing standards organizations. To compensate for this, the machinery drawings must be more detailed to assure that the true design intent is established. This typically requires more drawing sheets, again making the drawing package more difficult to check and to keep coordinated.

A New (Old) Idea

Many of the issues associated with modern engineering drawings can be addressed by developing designs using 3D parametric solid modeling programs. By this statement, I am not advocating a radical new idea but rather a shift back to the traditional "master layout" concept that has been used so successfully in the past. The only difference is that now a 3D solid model developed and maintained by a key design engineer will serve as the master layout. The specific software tool used is not critical -- the shift in design philosophy is what is important, and any number of modern software tools can be utilized to realize this goal.

Unlike the current 2D CAD tools most commonly used in today's design offices, parametric solid modeling software has been developed from the very beginning specifically for manipulating 3D solid models. Using these tools, the creation, modification and display of 3D geometry has become as quick and intuitive as creating 2D design data using 2D CAD systems. The parametric nature of these solid models allow for the rapid alteration of design geometry required during the design phase. This ability to quickly alter the solid model geometry is what sets parametric 3D design tools apart from the current 2D CAD software. While the traditional 2D CAD software has the capability of producing crude 3D surfaces and solid entities, the creation and modification of these entities is cumbersome and slow and does not support the needs of practical design engineers.

Using the new software tools, the design engineer can develop the design geometry quickly and can communicate the design direction with the project owners and other members of the design/analysis team long before committing the design to drawing sheets. Design intent can be readily demonstrated and understood by owners, maintenance personnel, operators and others who may not have the technical background to quickly understand traditional engineering drawings. Communication of the design can begin earlier in the design cycle and can be updated more often during the design effort. Relationships between adjacent systems can be better understood and explored, interferences between components can be more easily recognized and maintenance issues identified. As the design progresses and details begin to take shape, other advantages start to appear. The designer/analyst gets an accurate weight and CG for the system automatically. The designer can take advantage of pre-made detail parts available across the internet or through electronic databases. Space provisions required for bolts, hydraulic fittings, and other components can be more easily represented and understood. The actual fabrication sequence and organization of parts and sub-assemblies can be can be replicated (and therefore substantiated) within the structure of the master layout model.

Using these tools, engineering drawings are developed directly from the solid model and are linked at all times to that model – a change in the model is automatically reflected in the drawings. General arrangement, assembly and detail drawings can be established for the early design releases (example: 30, 60 and 90% PS&E releases) based on the level of detail contained within the master model at the time of the release. These views will automatically update as the master model is improved and the details of the design are finalized. Since all of the views are tied to the master layout it much less likely that there will be discrepancies or ambiguities within the drawing set. Sharing of the drawings can be accomplished electronically using neutral file formats such as Adobe's PDF files which can be viewed and printed using Adobe Acrobat Reader. They can also be translated directly to AutoCAD or Microstation file formats so that they can be utilized within existing drawing systems. In an ideal world, the 3D model could be part of the dataset released to the contractor in charge of fabricating the design, greatly improving the level of design definition available and simplifying the production of shop drawings.

How This Idea Has Worked

My first exposure to using this design philosophy was as a design engineer on Boeing's 777 aircraft. All aircraft developed prior to the 777 utilized a series design approach in which the airframe was designed first, then all of the systems were designed, and finally the structure was redesigned to accommodate the addition of the systems. On the 777 project the design of the airframe and all systems were conducted simultaneously using 3D solid models -- Boeing called this approach Digital Pre-Assembly (DPA). The engineering effort was divided into design phases. During the early phases estimates were made of the size and shape of each component as well as space required for assembly and maintenance. Models were prepared to represent the space requirements and were stored in a central database that everyone could access (i.e. the "master layout"). Space provisions were negotiated among the design staff until the needs of each design specialty was met. As the design progressed from one phase to the next, design details were gradually improved until they represented the final design configuration. The master database was always maintained with the latest design and weekly design reviews were conducted using a program called "fly through" which allowed the design team to literally walk through the complete design database and look for interferences and design issues.

In this program the advantages of the 3D data were significant. Processing the design of the airframe and the systems simultaneously eliminated the need to redesign the airframe to accommodate the systems. The ease of communicating the design intent to both technical and non-technical people allowed the designers to collect input from the personnel that would be fabricating, maintaining and operating the aircraft early in the design process and to incorporate changes into the design at the earliest stages to address the issues raised. The design approach eliminated the cost of at least three full-scale mock-ups which were traditionally used to design all earlier aircraft. Finally, the accuracy of the datasets (i.e. drawings) produced from the 3D solid models vastly improved the quality of the production tooling used to produce the aircraft, significantly reducing change, error and rework the 777's assembly line when compared with earlier production aircraft. This design process was so successful and the reduction in change, error and rework on the assembly line was so significant the Boeing actually went back and developed a complete 3D dataset for the 747 aircraft and then fabricated new production tooling based on this digital data.

While the use of DPA has proven to be very successful for Boeing, few of the projects that consulting engineers typically are involved with have the resources or the need for a design system as elaborate as that used on the 777 aircraft. To illustrate the power of 3D parametric design tools on a more typical heavy movable structures project I will use an example of an emergency repair made to the Passenger Overhead Loading System at the Bainbridge Island Terminal of Washington State Ferries.

The passenger overhead loading system at Bainbridge Island, Washington, pictured in figure 1, consists of a loading cab, supported by a lift frame, and positioned via a counterweight and hoist system. The Cab is positioned so that it can service both slips at the terminal and is connected to the terminal building via a passenger transferspan. Two movable aprons are mounted to the ends of the loading cab and allow passengers to board or disembark the ferry from the passenger deck, without interfering with vehicle loading and unloading. This system is critical to the ferry systems ability to maintain tight sailing schedules during the high volume morning and evening rush hours. Each apron can be

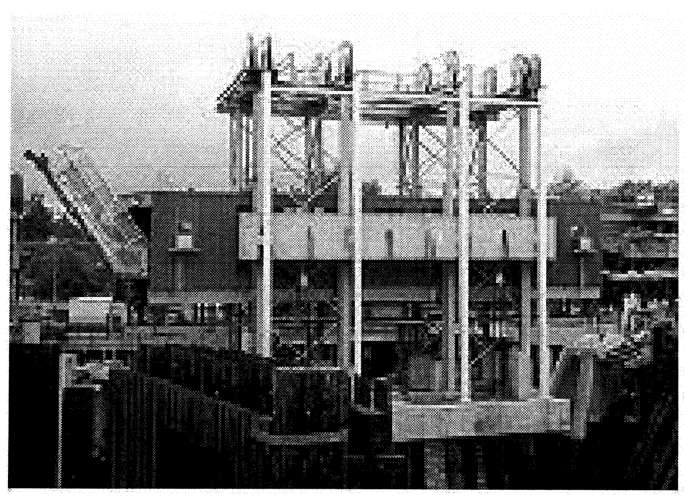

Figure 1 – Bainbridge Island Overhead Loading System

raised/lowered, slewed left or right and telescoped via hydraulic cylinders in order to accommodate specific boat configurations and tidal conditions.

The original hinge and bearing system for the passenger loading aprons was installed in the 1980s and had been operated multiple times per day with little problem since it was commissioned. In the fall of 2001, the apron for the north slip was damaged in operation and was removed from the overhead loading system. Upon inspection, the original pivot and lift bearing system showed signs of excessive wear and corrosion. Inspection of the second apron indicated that its pivot and vertical bearing system had similar wear and corrosion and that it would need repair in the near future. Rather than repair and reinstall the aprons as originally designed, it was decided to redesign the pivot and lift bearings to improve the system life. The design improvements had to be easily retrofitted to the existing apron and loading cab structure. Additionally the repairs had to be made very quickly because if the other apron had to be taken out of service for any reason, walk on passengers would have to load across the vehicle transferspan, greatly increasing the time required to load the ferry and therefore disrupting the ferry schedule.

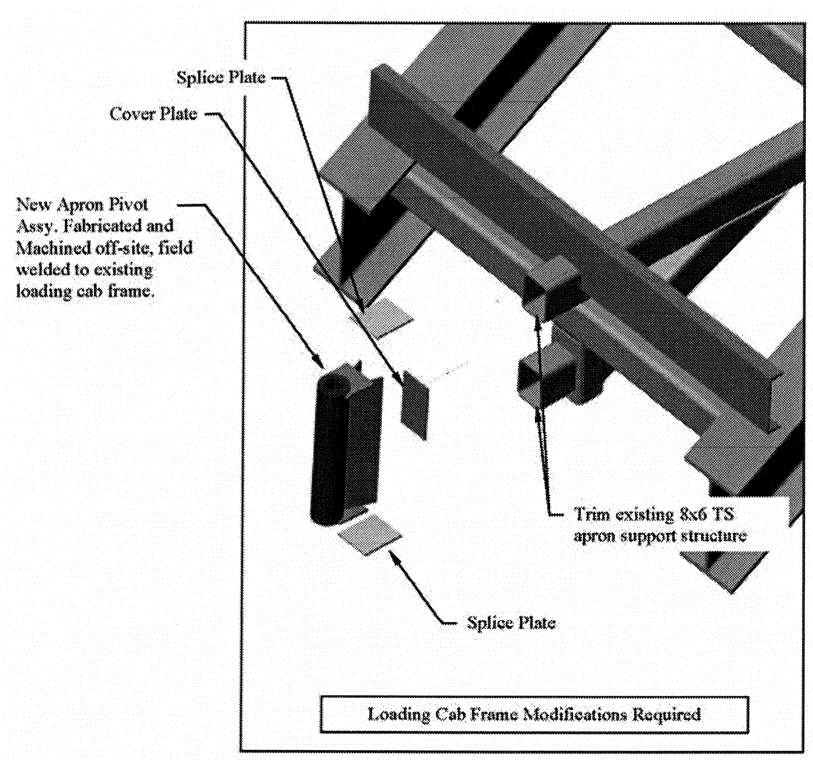

Figure 2 - Proposed Modifications to Cab Structure

The decision to use 3D parametric CAD software was initially made because of the need to quickly develop a new design and to insure that the design would fit the existing hardware once it was fabricated. Initial inspections of the apron and overhead loading cab were conducted on a Thursday afternoon and the recommendation to revise the existing design was approved by Friday afternoon. Using the original engineering drawings and field measurements of the existing apron and loading cab structure, a new pivot and hinge concept was developed over the weekend. By Monday morning the design team held the first meeting with the general contractor and specialty fabricator that would be performing the modifications. The figures 2 and 3 show some of the actual illustrations used to communicate the proposed modifications to the contractors during that first meeting. These renderings of the proposed modifications were created directly from the proposed new design geometry contained in the 3D Cad software. Based on the contractors input during this meeting the design was modified in order to simplify the required field welding on the loading cab frame. The solid model was updated to reflect the modifications and detailed design of the modifications started Monday afternoon. By Thursday afternoon the detail design of all modifications was complete (in the computer). A second meeting with the contractor was held that afternoon to go over the detail design. A list of critical and potentially long lead materials including the bearings and material for the pivot and hinge pins was released to the contractor at that time in order to facilitate early purchases. At that meeting the contractor expressed concerned with one of the proposed connections being added to the existing apron yoke structure. Based on the contractors concerns, the connection was modified. All of this occurred prior producing any significant drawings. Figures 4 and 5 below show the final "master layout" model that was produced for this project.

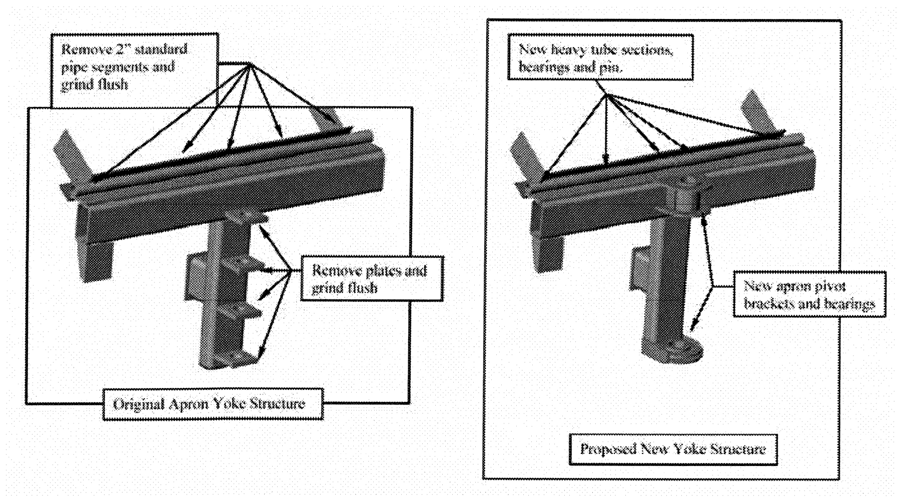

Figure 3 – Proposed Modifications to Apron Yoke Structure

With the design complete, the focus shifted to creating the engineering drawings required to fabricate and install the modifications. Because of the emergency nature of this repair, time was very critical. The detailed deign data imbedded in the solid model allowed us to quickly and accurately create shop level drawings directly from the master model -- the contractor fabricated directly to the engineering drawings without creating shop drawings. Because the drawing geometry was linked to the master model and the master model had been thoroughly checked against the actual field dimensions, the engineering team could be confident in the accuracy of the drawings. Once the master layout was complete and checked, all of the shop level drawings (40 – 11" x 17" sheets) were produced by a single engineer in less than one week. This would not have been possible without the use of the 3D modeling software. Typical drawing sheets are shown in figures 6, 7 and 8.

Using the drawings that we provided, the steel fabricator was able to produce all of the new components and to make all possible off-site modifications to existing components. No significant problems were encountered in this process and the fabrication was completed as designed. With new and modified components in hand, the general contractor performed all of the required field modifications and reinstalled the apron. The modified apron fit exactly as designed and performed as expected. Detailed monitoring of the modified apron during commissioning uncovered an additional, previously unknown, design flaw inherent in the original apron design. In order to eliminate this flaw and insure a long service life for the apron, an additional modification was quickly developed using the same approach. This modification was fabricated and installed without significant problems based on shop level drawings produced directly from the 3D cad data.

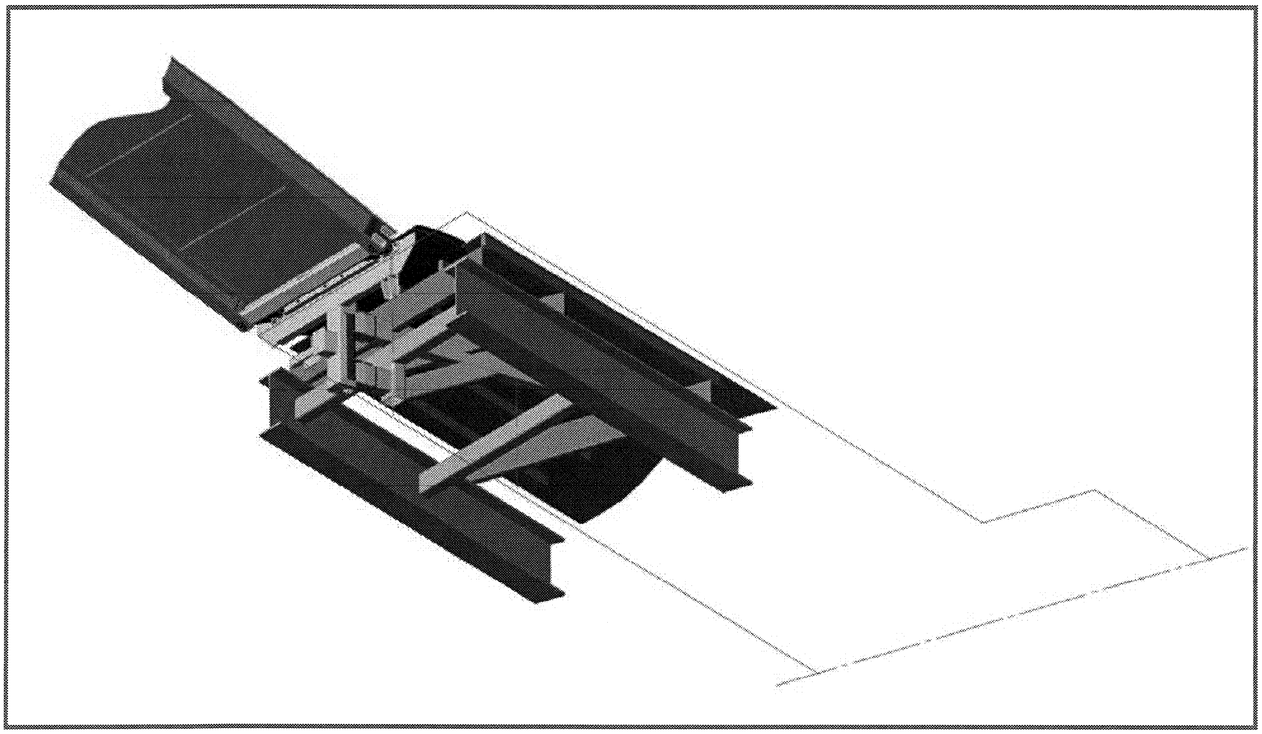

Figure 4 - Master Layout Model

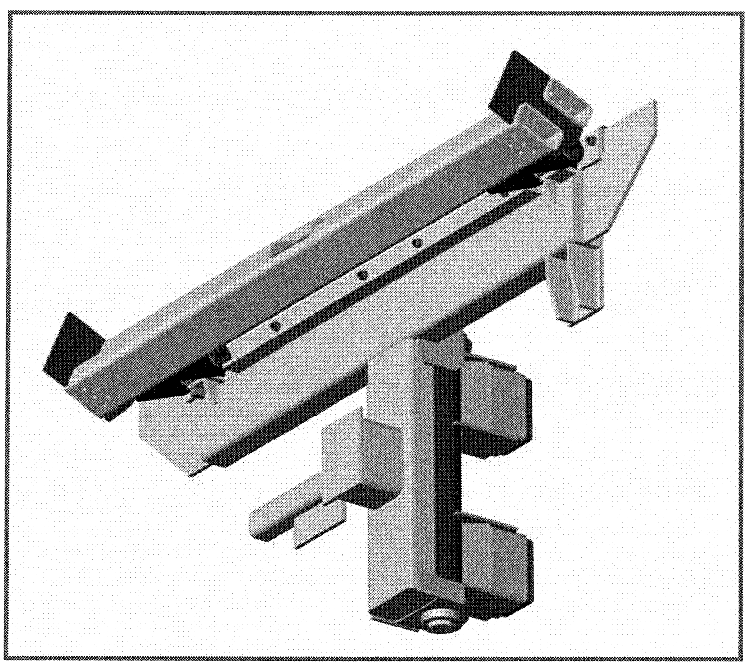

Figure 5 - Master Layout Model Details

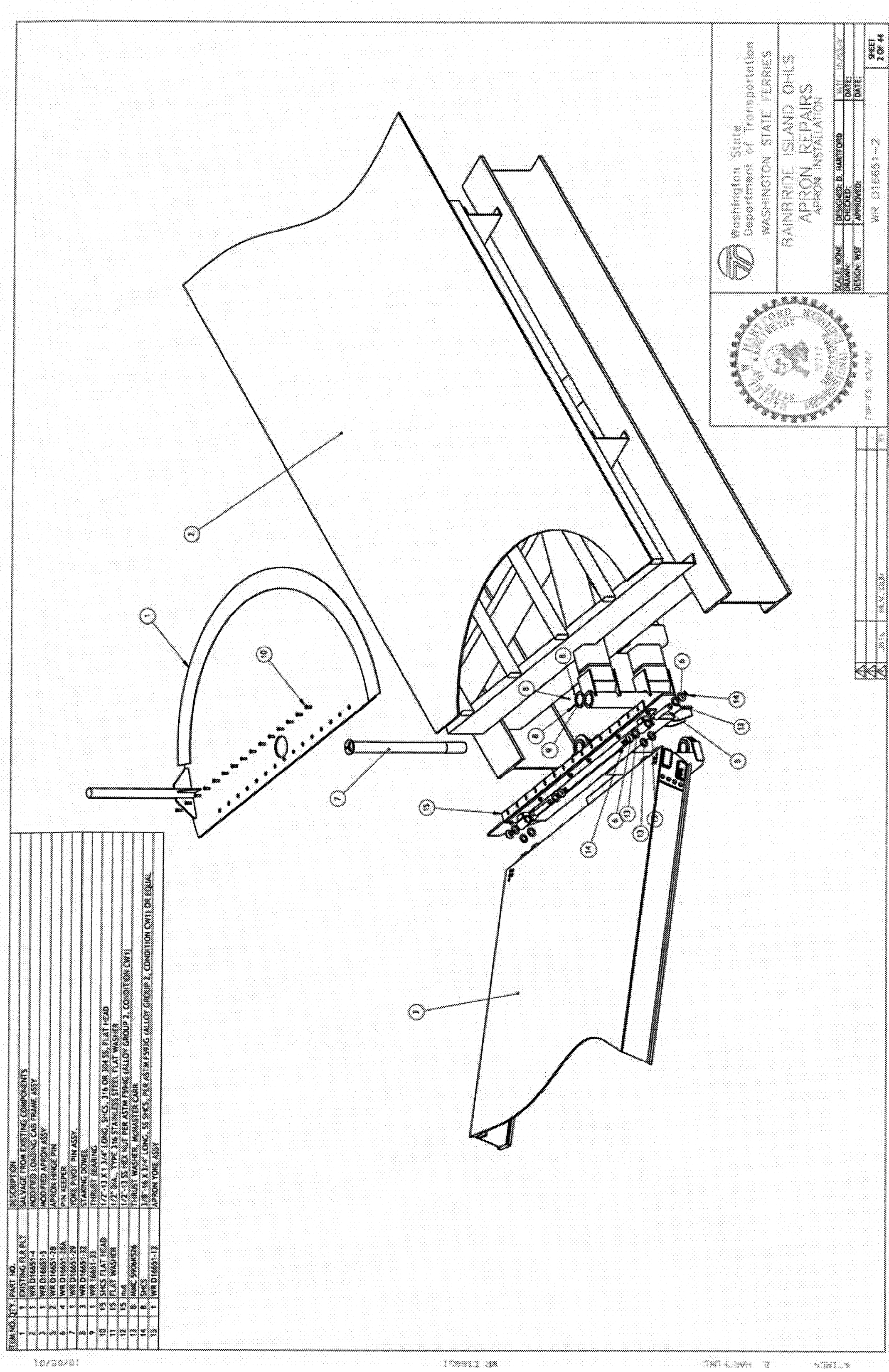

Figure 6 - Typical Assembly Drawing

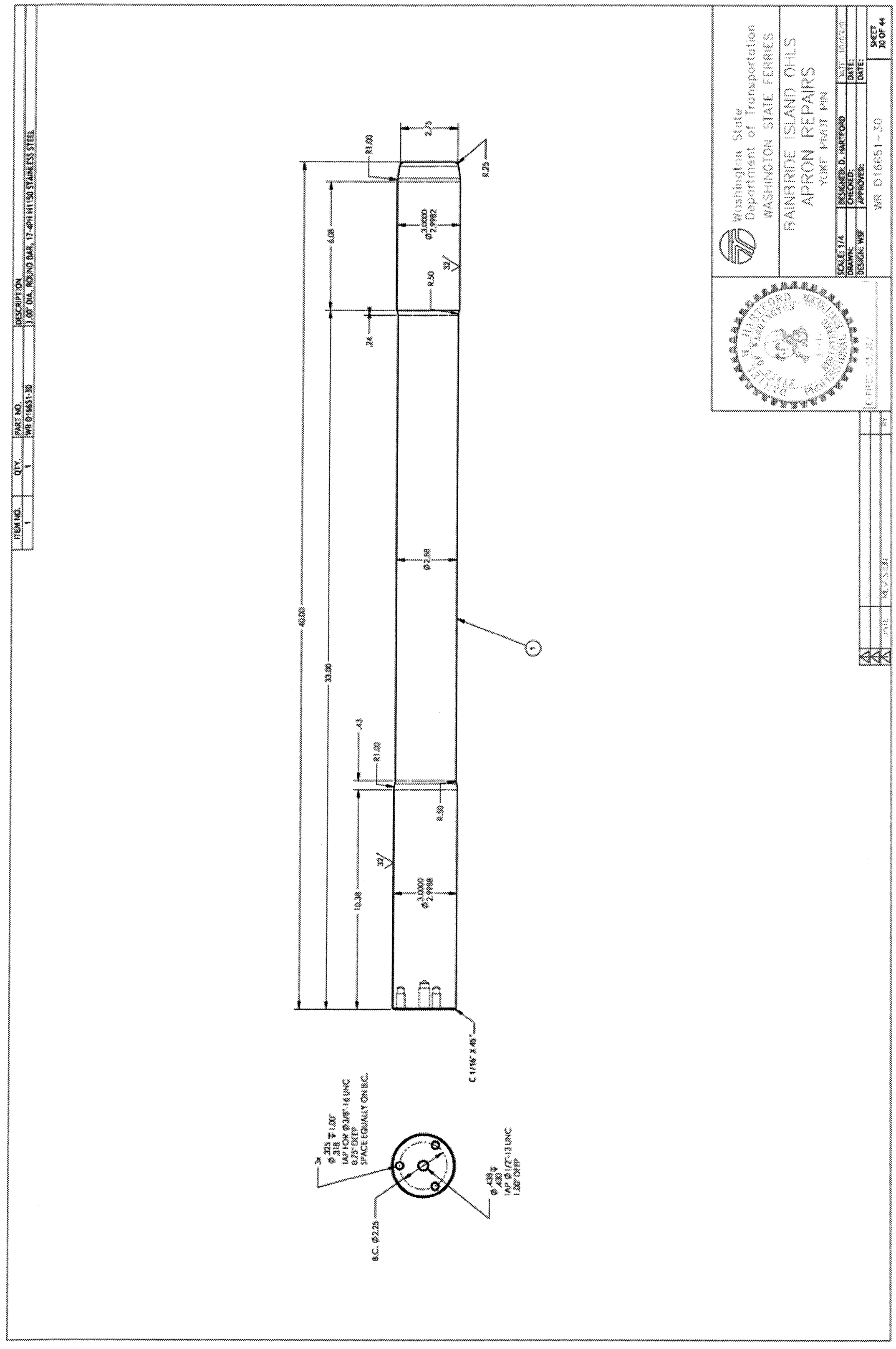

Figure 7- Typical Detail Drawing

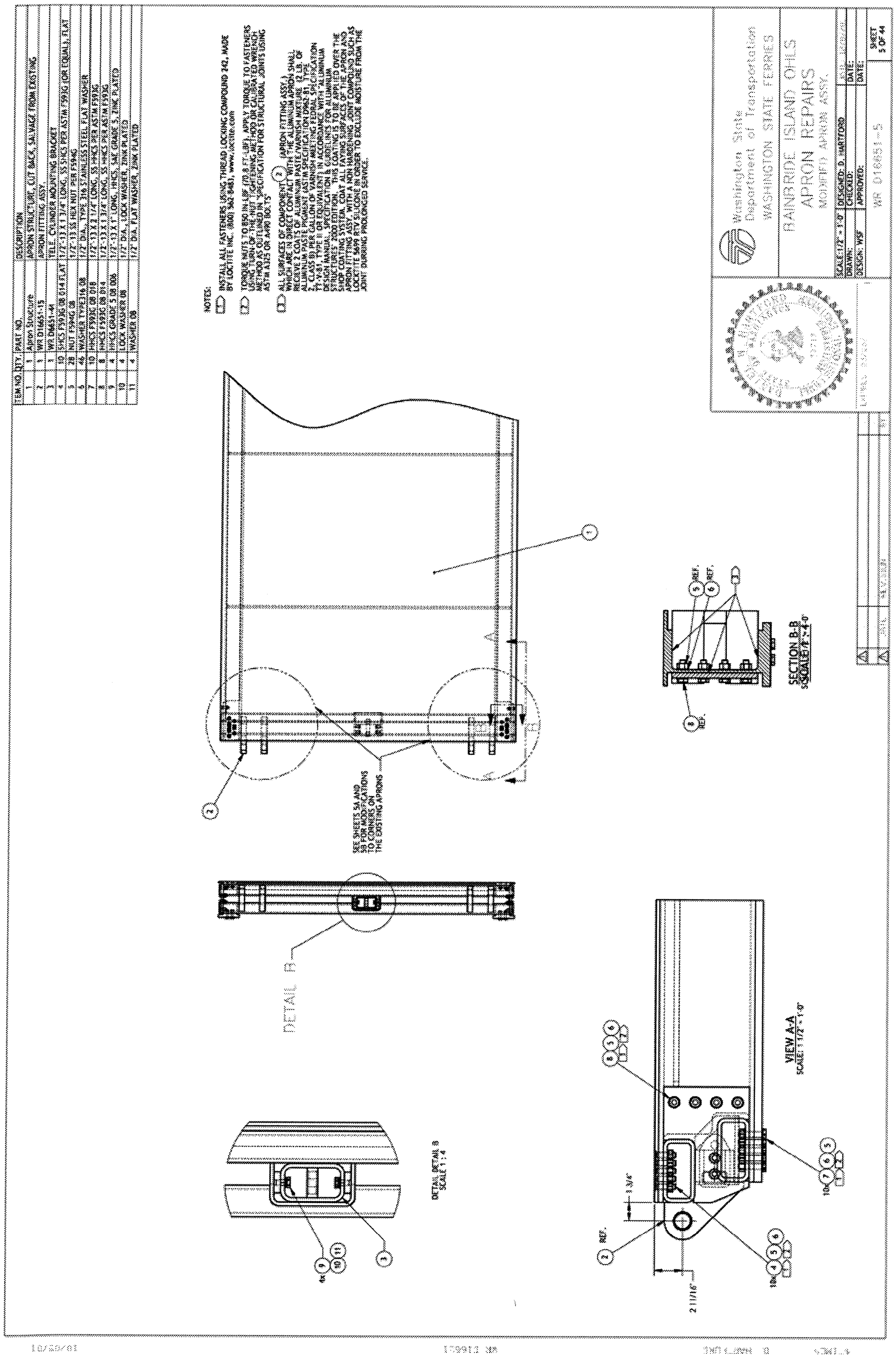

Figure 8 - Typical Assembly Drawing

Advanced Finite Element Analysis

Finite Element Analysis – The Tradition

Since its introduction in the 1960's the Finite Element Method (FEM) has become an instrumental analysis tool for structural engineers. FEM allows complex, statically indeterminate structures to be quickly and easily analyzed and provides the structural engineer more complete understanding of how the structure is responding to the given loads.

The major drawback to traditional FEM is that significant engineering judgment is still required when applying boundary conditions to the model. This shortcoming is exacerbated on heavy movable structures because of the complex interactions between the mechanical systems and the structure. On these structures the boundary conditions are often dictated by mechanical components such as bearings. Bearing stiffness, mechanical clearances, bearing friction and structural flexibility all contribute to the difficulty in making accurate assumptions. Errors in these assumptions often lead to critical loads being overlooked, improper design of bearings, excessive wear on bearings and drive components, increased hoist or drive loads and system instability. In extreme cases these errors can lead to significant redesign of the system after the initial commissioning or even to catastrophic failures of the structure.

Often these boundary conditions can be addressed by the mechanical design engineer by carefully selecting bearing and drive components that will insure a particular boundary condition exists. The downside to this approach is a design more complex than it needs to be, increased initial costs and ongoing maintenance cost over the life of the system. Additionally, the design engineer may be subject to physical constraints on a particular design that will not allow the use of the preferred components. Ideally, the engineer would select the best solution for a particular design problem rather than the solution that produces the simplest computational model.

Contact Elements – A New Approach

Recent advances in FEM technology and computational capacity have provided designers with powerful new tools to study the interaction between structures and mechanical systems. Using these tools designers can gain a much better understanding of the true boundary conditions inherent in a particular design and how the performance of specific components within the design will be affected.

The key technological improvement making this approach possible is the introduction of surface to surface contact elements that are easy to define and that take into account friction between the contacting surfaces. Using these elements, along with high order solid elements, allows components like bearings and pins to be modeled accurately. These elements can then be tied to the more traditional structural model (beam and shell elements) using constraint equations.

Figure 9 below shows a FEM model of a spillway tainter gate utilizing contact elements. In this model, the trunnions, hubs, bearings, thrust bearings, pins and yokes, are all modeled as separate components using 20 node brick elements. The brick elements for these components are generated using automatic meshing algorithms on top of 3D solid and surface data. All significant geometric data such as the press

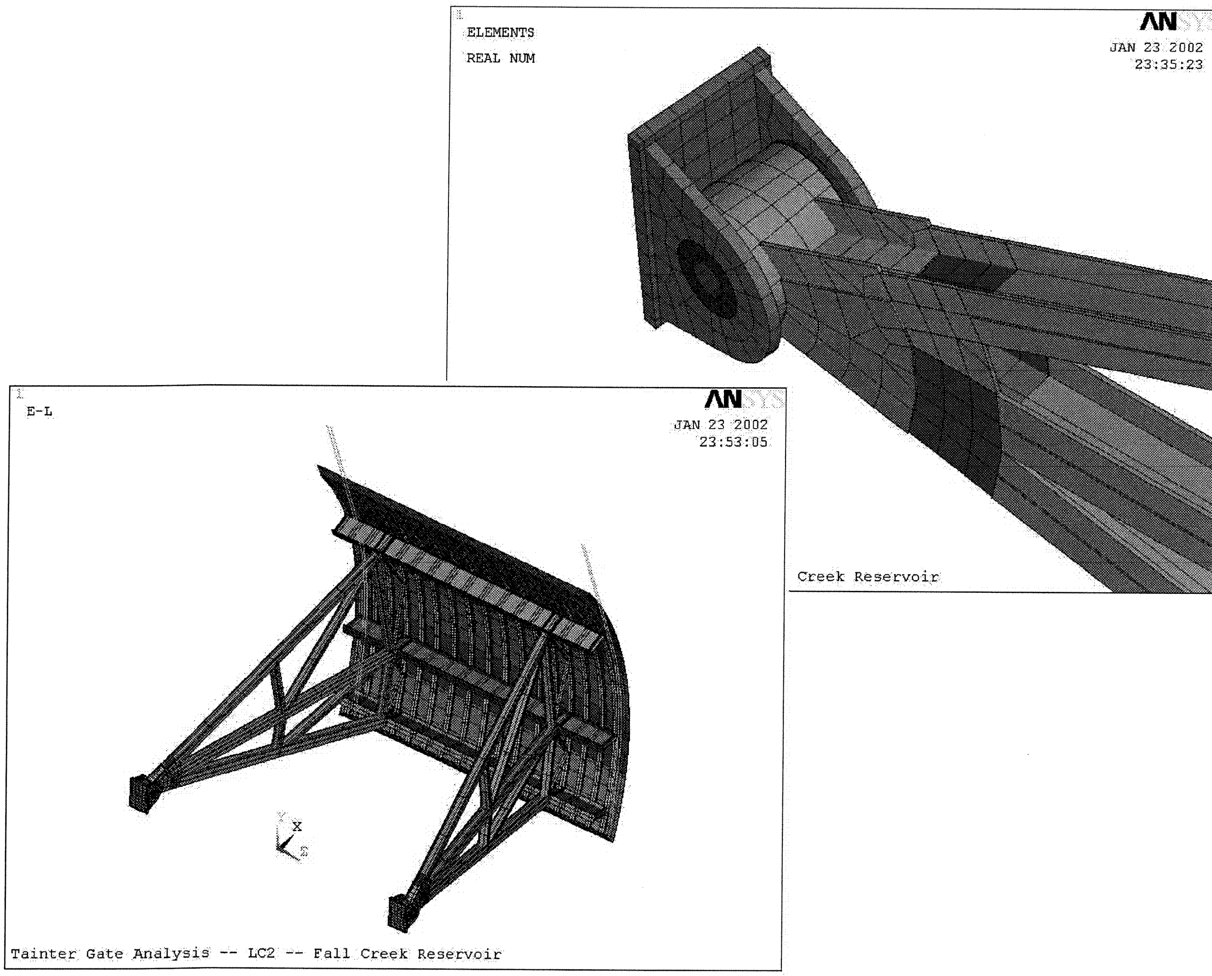

Figure 9 - Tainter Gate Model With Contact

fit of the bearing into the trunnion hub has been incorporated into the base geometry and the effects of these details will be included in the analysis. The contact elements that tie all of the separate component meshes together are automatically generated based on the 3D surface data using surface-to-surface contact algorithms. Boundary conditions representing the pier walls are applied directly to the yoke structures, and the model is allowed to calculate the distribution of forces within the bearings. Gate hoist ropes are modeled and contact between the ropes and the face skin of the gate is included. Hoist loads are applied to the gate by displacing the end node of the hoist wire rope to represent the hoist winch raising or lowering the gate. The contribution of the hoist rope loads to the bearing forces is automatically accounted for by the reaction of the hoist rope elements against the shell of the gate. The model automatically calculates effects of trunnion friction based on the contact force between the pins and bearings and the coefficient of friction input for the contact elements.

Most tainter gates design prior to 1970 did not include trunnion friction as a design load for the gate structure. Eventually damaged gates and several catastrophic failures proved to designers that trunnion friction loads should not be neglected in the structural design of the gate. Even after this was recognized, trunnion friction loads were significantly underestimated because designers did not fully account for the boundary conditions established by the trunnion bearings and the thrust bearings. The model shown in

Figure 9 would have automatically accounted for all of the additional loads developed due to trunnion friction and would have given the designers a chance to improve the design to accommodate those loads prior to fabrication of the gates.

Figure 10 shows a FEM full model of an aftermarket excavator stick and a second model of the stick pivot and surrounding structure. The manufacturer of this stick had been having dificulties with the stick pivots wearing out prematurly on other boom models and wanted to eliminate this on their new products.

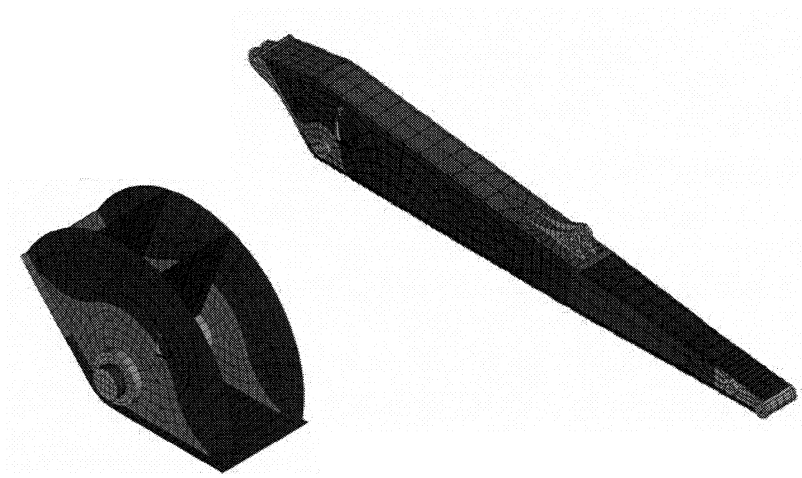

Figure 10 - Stick FEM Models

The full model was used to identify and eliminate stress concentration in the global stick structure and to determine the loads that should be applied to the stick pivot sub model. The stick pivot model utilized contact elements between the pivot bore and the pivot pin to accurately represent the boundary conditions inherent in the bearing and pin design. This model was solved for the critical load conditions and the results indicated that significant edge loading of the bearings was occurring, causing a substantial increase in the peak contact stresses between the pin and the bearing bore. The nominal pin size was increased until the peak contract stresses were within reasonable limits and the new stick design went into production with the larger pivot pin. To date there have been no reports of significant bearing or pivot pin wear on the new stick. Figure 11 below shows some of the typical output that can be obtained from the FEM program. In the top left hand box we see a plot of the contact pressure distribution on both pivot bearings. The center box shows a close-up of the right hand pivot bearing. This plot shows the distribution of contact pressure on the bearing surface and also shows that a path has been defined on the bearing surface parallel to the bearing axis. Finally the lower left hand plot charts the variation in bearing pressure along the defined plot path.

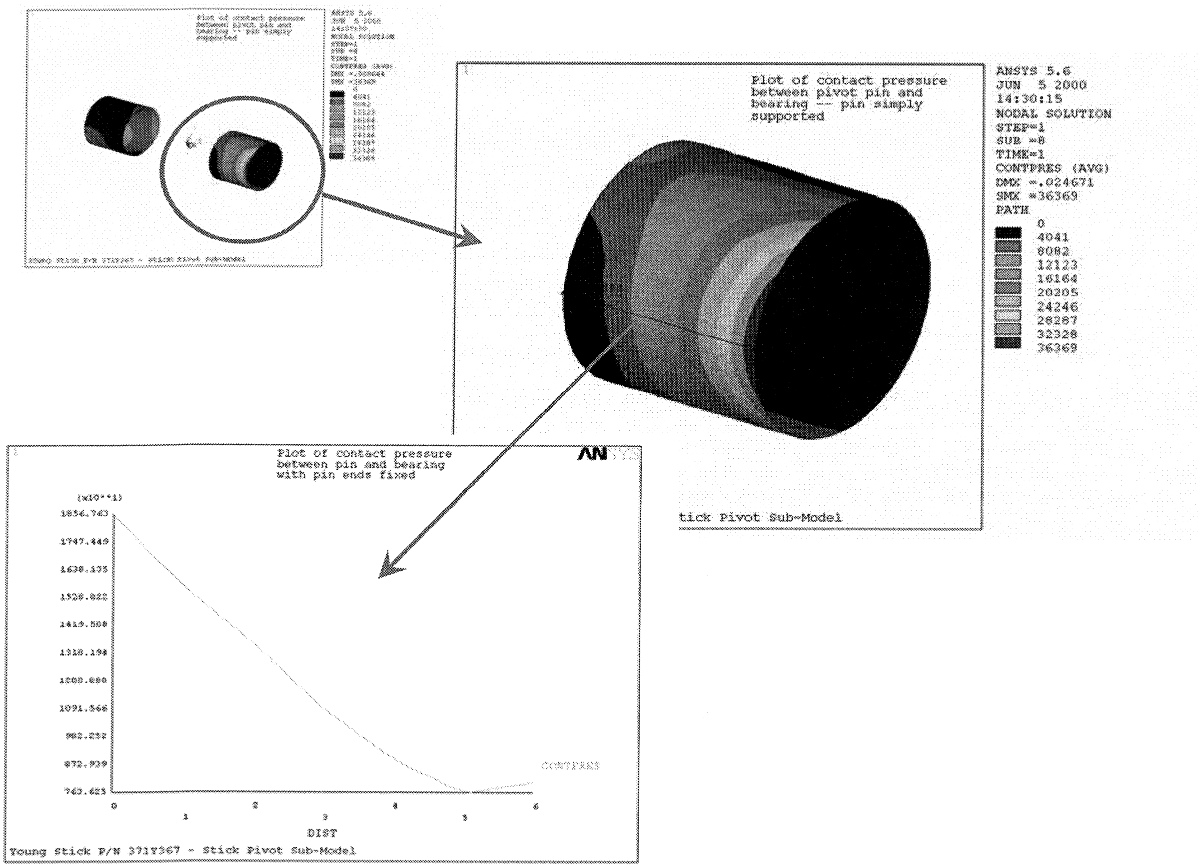

Figure 11 - Typical FEM Output

3D Kinematic/Dynamic Modeling

Kinematics/Dynamics (i.e. "Virtual Prototypes")

3D Kinematic/Dynamic modelers are the newest and the least developed of the three engineering tools I am discussing in this paper. The idea behind these tools is to simulate the actual operation of a machine, to explore its performance and to investigate its response to external inputs -- all on the computer prior to building the physical machine. This methodology has often been termed "Virtual Prototyping".

These tools were initially developed to aid in the design of dynamic systems in the aerospace industry. They have now been extensively employed in the design and development of automotive and truck suspension systems and in the prediction of vehicle handling characteristics. More recently these tools have been employed to study the performance of industrial robots and heavy equipment such as excavators and cranes.

Kinematic modeling programs are different from the FEM tools discussed above in that they are intended to study systems that undergo large displacements occurring over a relatively long period of time (say 1 to 60 seconds). These analysis tools are very efficient at solving this kind of problem because the moving system is represented as a discrete number of rigid bodies tied together via idealized joints and operated on by idealized actuators. With this approach the number of variables that the program must track during the solution is kept small and the complexity of the equations of motion which describe the system is kept to a minimum. The downside is that results data is only available for discrete locations (ex. force data as a function of time is available at any joint) whereas the FEM tools provide continuous results data for the entire system.

Applications in Heavy Movable Structures

To my knowledge, these tools have seen very little application to heavy movable structures problems. Until recently the tools have been quite expensive. They were also so complex that they required a full time dedicated analyst in order to be used effectively. Recently several companies have produced low end products that are less expensive and are designed to be quickly mastered by the casual user. These new tools are very powerful and are closely integrated with the 3D solid modeling tools discussed earlier. They utilize the 3D cad data to define rigid bodies for the model and then allow the engineer to quickly define the kinematic relationship between these bodies using idealized joints. Weights and CG's for the rigid bodies can be calculated automatically based on the geometry and the component density or the engineer can manually override this function and enter the data by hand. Idealized actuators can be added to represent real mechanical actuators. The force and displacement of these actuators can be tailored to math the performance characteristics of the real actuators. Where motion of a body is limited by contact with other components, idealized contacts can be placed to prevent the moving body from passing through the interfering components. These contacts will also estimate the impact loads created when contact occurs.

Once the model is set up the engineer can quickly and easily run any number of simulations simply by establishing the system initial conditions at the beginning of the simulation and defining all external inputs operating on the system. The motion of the system is displayed on the screen during the simulation and this data is saved in a video file to aid the engineer in understanding the response of the system. All system state information (displacements, velocities, accelerations, forces, etc.) can be plotted as a function of time after the simulation has been completed. This is a very powerful tool that, if used properly, will allow the engineer to have a much more complete understanding of the performance of the system over the entire range of motion. If the design engineer has a more complete and thorough understanding of the system being developed, then the risk that the system will not perform as expected in service is reduced.

While these simplified tools are quite powerful, they have unfortunately dropped one capability that is, in my estimation, critical if these tools are to be useful on certain types of heavy movable structures problems – the ability to use a flexible body as a kinematic component in place of a rigid body. Because of the physical size of the moving components in heavy movable structures, flexibility of one of the components will come to dominate the response of the system. When this is the case it is critical to include the flexibility of this component in the definition of the model. In order to include this flexibility the high end engineering tools must be used.

One HMS Example

To explore the usefulness these tools on heavy movable structures and to illustrate how they might be employed I prepared the following example analysis. This example is based on a real world problem that I encountered when evaluating the safety of an existing Washington State Ferry passenger overhead loading system. This system is roughly illustrated by Figure 12 below and consisted of a long, steel truss transferspan, supported at one end by a fixed bridge seat and hoisted at the other end via a pair of hydraulic cylinders mounted to a lift frame outboard of the transferspan. A large loading cab structure

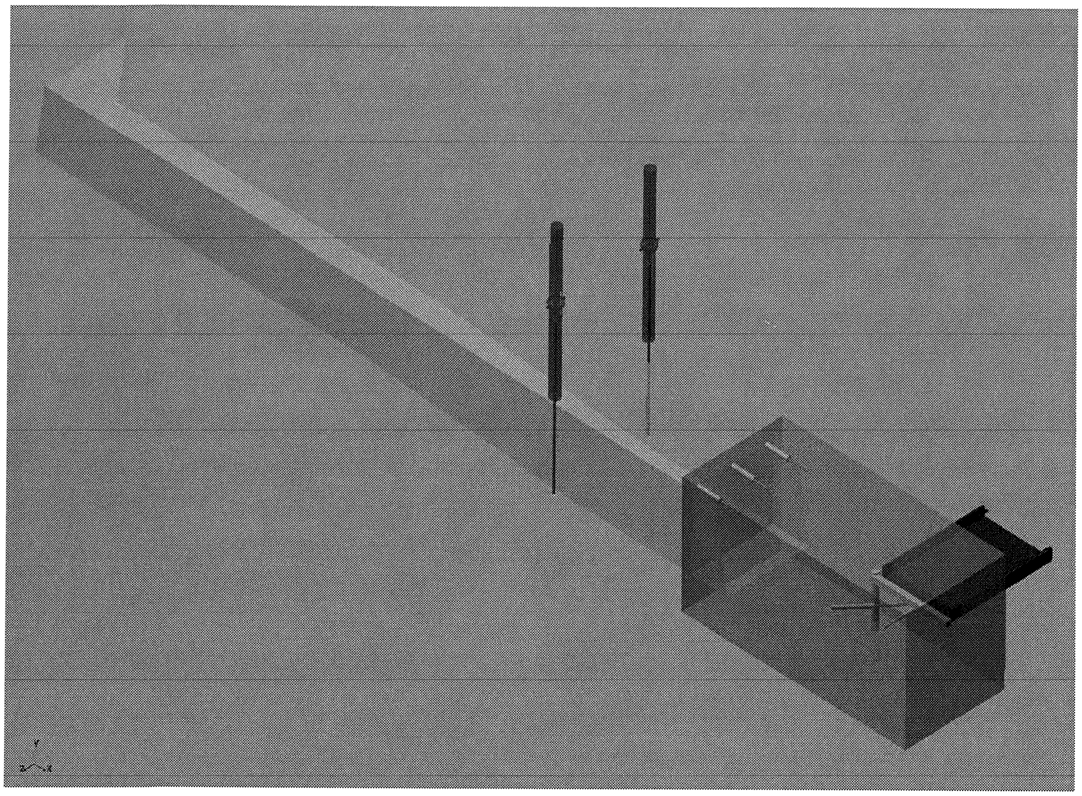

Figure 12 - Overhead Loading System Model

was mounted to the end to the transferspan with a pined type connection located below the floor of the cab. This connection allowed cab to rotate relative the transferspan. Three hydraulic cylinders mounted above the roof of the loading cab connect the loading cab back to the top of the transfer span and prevent the cab from drooping into the water. The cab is kept level throughout the entire range of motion of system by adjusting the length of these three cylinders. A large, hydraulically operated apron hangs off of the left had side of the loading cab.

The question that I wanted to answer with this model was quite simple, given the specific design configuration; assume that the rod of the left hand hydraulic cylinder fails catastrophically – what is the maximum load the remaining hydraulic cylinder would need to carry? The design variables that are critical to this analysis are the mass and center of gravity of the transferspan, loading cab and apron, the location of all joints, the stiffness and damping characteristics all cylinders and the flexibility and damping of the transferspan structure. Because the flexibility of the transferspan is critical to the response of the system, it was modeled as a flexible body that was developed in a finite element program and imported into the kinematic/dynamic modeler. The loading cab, aprons and cylinders were all modeled as rigid bodies. All components were tied together using spherical joints to form the rotating constraints (pin joints) and sliding joints to form translational constraints (cylinders telescoping). Performance of the hydraulic cylinders under load was modeled using an idealized cylinder model standing on a check valve (see Figure 13). This system was set up and a simulation run was made with both lift cylinders sharing the load in order to establish the initial conditions for the next simulation. A second simulation was then run covering a total of ten seconds. At 0.1 seconds into the simulation, the

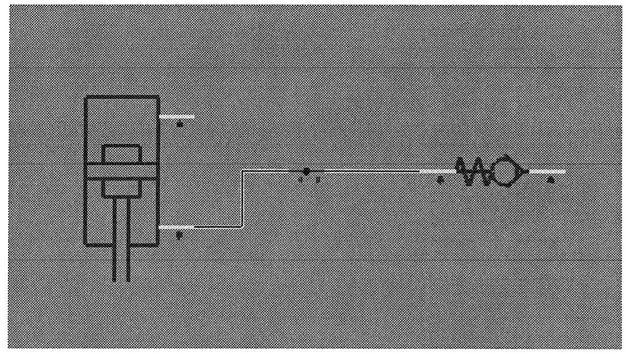

Figure 13 - Hydraulic Cylinder Model

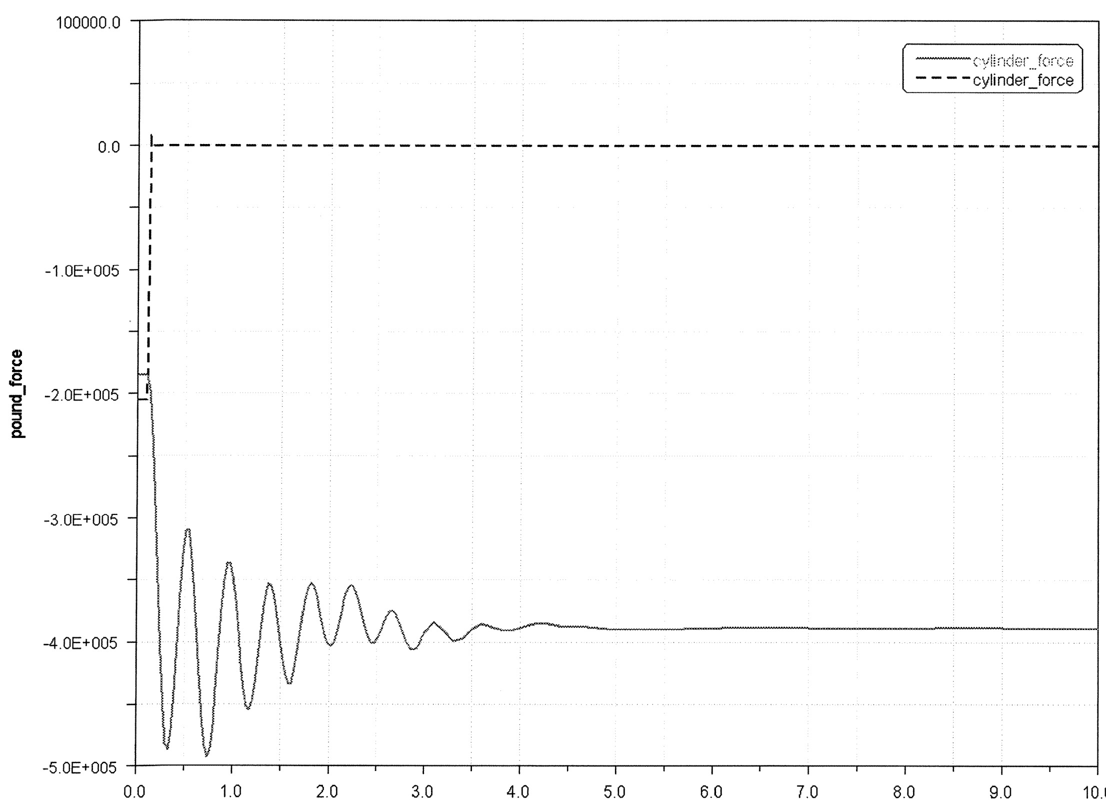

Figure 14 - Simulated Lift Cylinder Loads

joint of the left-hand lift cylinder was released to simulate a sudden failure of the cylinder rod. Figure 14 shows a plot of the lift cylinder loads verses time for this simulation. At the very beginning of the simulation both cylinders carried nearly identical loads with the left-hand cylinder (blue curve) carrying slightly more than the right-hand cylinder because of the weight of the apron hanging out to the left. At time equals 0.1 seconds, the left-hand cylinder load suddenly drops to zero and the load on the right hand cylinder increases. As expected the load rises sharply, initially overshooting the total load initially carried by both cylinders and then slowly damping out to the new steady state load of approximately 395 Kips. This process was predicted to take approximately 5 seconds to complete and the maximum load that the hydraulic cylinder carried was around 490 kips or roughly a dynamic magnification factor of 1.26.

Conclusions

In this paper I have discussed three distinct families of modern engineering tools. I have explored how each of these tools could be used to aid in the design and analysis of heavy movable structures, and I have investigated the potential benefits that could be realized if these tools were made an integral part of the design process. I have also provided specific examples to illustrate the use of each group of tools on HMS type problems.

At this point I need to stress that these amazing computer programs are nothing more than engineering tools. They will never replace sound engineering judgment or the crisp and creative thinking of good design engineers. If these tools are adopted but then not integrated into a well thought out, systematic design process, the quality of the designs will most likely decline. Without the structure of a systematic design process the design engineer can easily be distracted by the power of these tools and fail to spend adequate time considering design alternatives, thinking through the repercussions of each design decision or considering the methods by which a particular design would need to be fabricated and installed.

If used correctly these tools provide considerable benefit. Communication between the designers, owners, contractors and maintenance staff will be improved and the process of communicating design ideas will begin at a much earlier stage of the design. More of the designer's ideas will be captured and stored with the design dataset (master layout model). The design drawings will be produced from and linked to that same design dataset, reducing the chances that the drawing package contains errors or ambiguity. The advanced analysis tools will significantly improve the designer's understanding a design's performance and will also tend to uncover unanticipated characteristics inherent in each particular design.

If these tools are adopted as an integral part of a carefully planned design process, then they hold the promise of dramatically improving the quality of engineering.