COLOSSAL TOOLING DESIGN WITH 3-D SIMULATION

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When you need a huge tool to manufacture something huge, simulation and ergonomic analysis are critical to ensure worker safety.

TYPICALLY, THE DESIGN OF MANDREL-TYPE TOOLING for composite layup (the application of distinct layers of various clothlike materials with a bonding agent, an example being Fiberglas) is straightforward and has little effect on worker ergonomics. However, designing a colossal mandrel-type tooling for manufacturing aerospace fuel tanks that range up to 40 feet in diameter and more than 100 feet in length presents extraordinary ergonomic and physiological challenges. The mandrel tool for fabricating these flight-ready, reusable composite tanks is estimated to weigh 400,000 pounds, and the tool must be disassembled and carefully removed from inside the completed composite tank shell.

To assist in the human engineering analysis, engineers and designers used advanced three-dimensional (3-D) or virtual reality (VR) simulation tools. Ergonomics and human factors ramifications for the design of this colossal tooling are critical because worker's health and safety are at stake. In addition, this state-of-the-art analysis methodology can save costly mistakes while the design is still in digital form, eliminate time-consuming and expensive mockups, and provide critical ergonomic analysis and information.

The greatest challenge for the workers who must function inside the assembled hollow tooling is the disassembly process. This process must be accomplished by systematically removing tooling segments in order to release the completed composite tank from the outside of the colossal tool. This situation presents a unique set of problems for human factors specialists who utilize high-level 3-D simulation software to generate simulated human workers to carry out anticipated tank disassembly tasks. In this article, we describe the 3-D ergonomic simulation, analysis, and results of this research.

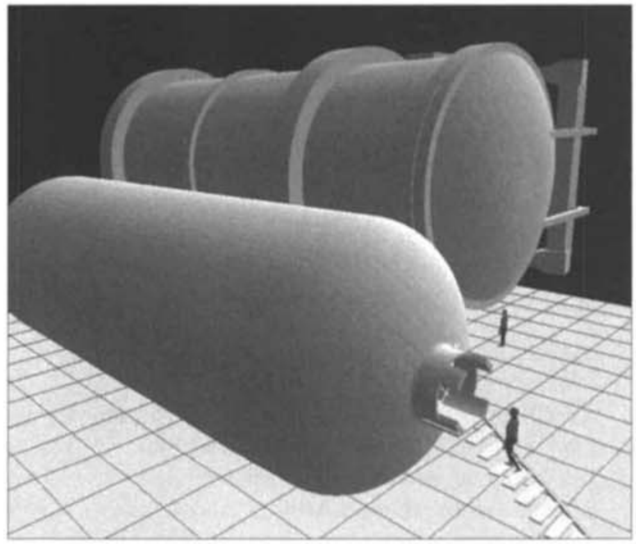

Figure 1: Colossal tool overview: mandrel tooling in foreground with autoclave behind.

SCOPE OF THE TOOL

Schaub and colleagues (1997) stated that preventive health care is one of the basic challenges facing ergonomists. In manufacturing, typically some human factors/ergonomics (HF/E) issues must be considered during one or more tooling design and utilization phases. These applied human factors include, but are not limited to, reachability, visibility, lift factors, kilocalorie usage, repetitive motion, ventilation, and lighting. When the tool size becomes colossal – say, 35 feet or more in diameter and 90 feet or more in length – and the tool weighs an estimated 200 tons, these normal human engineering factors may become critical to the safety and health of the workers (see Figure 1).

It is no small task to manually disassemble a mandrel tool that is surrounded by the finished composite shell, especially when its individual segments weigh up to 2400 pounds. In addition, removal of the tool segments must be completed extremely carefully to protect not only workers but also the thin, relatively fragile finished composite shell surrounding the tooling. This disassembly effort is to be completed in a confined space that may contain material outgassing, poor ventilation, and poor lighting. Furthermore, the disassembled tooling segments must be removed from the composite shell through a opening less than six feet in diameter. The sheer enormity of the tooling assembly and, especially, the disassembly operation takes human engineering in manufacturing system design to new vistas.

Diehl, Gawron, and Canham (1997) described how 3-D simulation was originally developed partly to address the sometimes great expense and danger of designing and testing complex systems. As early as 1995, Nayar (1996) warned the manufacturing world not to ignore the use of high-level, computer-generated graphical HF/E engineering aids during the product and tool design stages. This is especially true when designing colossal tooling. 3-D simulation to assist in decision making during the tooling design phase is extremely important and cost-effective. It affords design and HF/E engineers the opportunity to visualize and carry out various mechanical and ergonomic analyses along with "what if" scenarios.

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The human engineering tools in the Delmia ENVISION ERGO software package, which we employed for this simulation, can be used to accomplish analyses that can provide detailed information on load and stress situations, which may affect the executability and tolerability of work situations (Schaub et al., 1997). Analysis and information gathering can be completed while the design is still in the digital state. Therefore, the design can be examined and tested without exposing workers to potentially dangerous situations and saves the organization the time and expense of physical mockups.

LITERATURE REVIEW AND SOFTWARE SELECTION

As early as 1992, engineers and human factors specialists began using computers during the design of complex systems to investigate how the human/machine interface in these systems could be improved. Scanlon (1992) reported using computer-aided design (CAD) and human factors engineering to improve the maintainability of aircraft engines by aircraft maintenance personnel.

Research regarding the utilization of 3-D or VR simulation for the design and ergonomic analysis of extremely large tooling used as a mold or mandrel for composite layup is nonexistent. Several papers illustrate the use of computer simulation for testing of composite laminates. Krueger and O'Brien (2001) described a shell/3-D modeling technique development using a 3-D solid finite element model for testing composite delamination. Aono et al. (1994) reported that 3-D simulation has been used as a modeling and optimization tool to fit composite woven fiber to curved surfaces, but they did not mention the use of 3-D simulation for tool design or human engineering analysis.

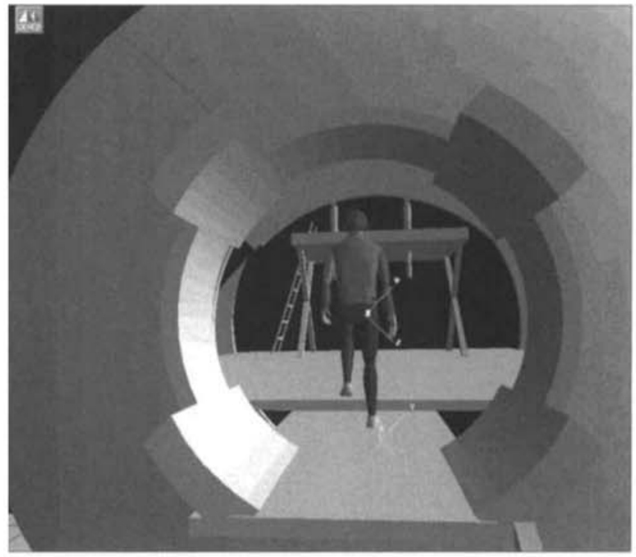

Figure 2: Tank tooling opening.

Sundin (2001) described participatory ergonomics using 3-D computerized simulation as a means for improving both workplace design and product development. This approach utilizes people – especially workers directly involved in the process or area being studied – to work with manufacturing or design engineers during the design stage to improve the ultimate product. Diehl et al. (1997) related how 3-D simulation was developed partly because of the expense and hazards of testing and evaluation of complex engineering projects. However, they did not report any utilization of computerized 3-D or VR simulation for modeling or human factors evaluation or analysis of large tooling in manufacturing.

To human factors/ergonomics professionals, integrating knowledge gathered from human engineering research as early as possible in the design of a product or system is an ultimate objective. It permits the researcher to reap the greatest benefit for the least outlay of funds (Feyen, Liu, Chaffin, Jimmerson, & Joseph, 1999). Several commercially available software programs are capable of carrying out reliable ergonomic analyses. The software we used for the ergonomic analysis of the colossal tooling design was ENVISION ERGO developed by Delmia Corporation in Auburn Hills, Michigan. The high-level graphics software has an array of analytical tools designed to be used with anthropometrically correct computer-generated digital humans. This sophisticated tool was central to the ergonomics analysis reported in this research.

The selection of ENVISION ERGO analytical software package for this project was based on previous research into the complex interaction of manufacturing system design

(Hunter, 2002) and its effect on worker ergonomics and physiology. We selected Delmia's ERGO because it is user-friendly, powerful, and fast and has a variety of ergonomics and 3-D simulation and analysis tools. ERGO proved itself on every criterion in our selection process.

MEETING THE CHALLENGES OF TANK SHELL MANUFACTURING

In the typical composite layout manufacturing sequence for a cylindrical tank, the composite material is wrapped in thin alternating layers around a spinning mandrel of proper shape. After wrapping, the composite-covered mandrel must be autoclaved for composite curing. (In the case of the huge fuel tanks described here, the mandrel tool may have additional composite layers added. Thus, after each wrapping cycle, the composites must be autoclaved for curing.) The mandrel may be manufactured from various materials, but it must have the strength to withstand the composite laminate wrap crush forces and the curing temperatures of the autoclave. The mandrel designs must provide for ease of removal of the forming mandrel after the composite/resin application and curing cycle has been completed. After final curing, the mandrel tool and the composite shell must be separated.

It became clear that special tooling segment removal equipment and material handling devices would be critical to the success of this manufacturing process.

For core removal, typically the mandrel is collapsed, washed out if disposable material is used, melted out if eutectic material is utilized, or disassembled by a number of other methods and subsequently removed from the composite shell. At this point in the manufacturing sequence, the composite shell is completed or at least ready for secondary operations. In the case of colossal mandrel tooling, the mandrel may be composed of several hundred to several thousand longitudinally interlocking tooling segments.

Tooling segment removal is a complicated and potentially dangerous process. With an internal diameter in the range of 35 to 40 feet and with mandrel tooling in a horizontal orientation, manufacturing engineers are faced with a disassembly operation that puts workers at heights up to four stories. This, combined with tool segments weighing up to 2400 pounds, requires specially designed material-handling equipment.

The tooling segments are removed beginning at the 12 o'clock position with the keystone tooling segment being removed first. The uppermost segments can be lowered almost vertically to the tank's horizontal centerline. However, in our 3-D simulation of this part of the disassembly task, we found that as subsequent segments are removed, they are displaced farther from the vertical position. The removal path becomes more horizontal as the disassembly process proceeds toward the 9 o'clock and 3 o'clock positions. Consequently, the removal equipment must increasingly adapt to segment removal from a horizontal position rather than from a vertical position. The opposite situation occurs as the workers pass the 9 o'clock and 3 o'clock positions. Ultimately, the processes progress to segments located at the 6 o'clock position. The removal process then changes to a vertical lift in order to position tool segments on the tank's horizontal axis for removal to the outside via the narrow opening.

When we used 3-D simulation to analyze this situation, it became clear that special tooling segment removal equipment and material handling devices would be critical to the success of this manufacturing process. The removal equipment was divided into two categories. In the first was equipment and material-handling devices to disassemble and transport tooling segments to the tank centerline. The second category of equipment included machinery and material-handling equipment for transporting tooling segments from the composite tank centerline and then outside to a storage or assembly area adjacent to the tank. This was no small undertaking, considering the large tooling segments that must be moved at least half the length or more of the roughly 100-foot-long tank. In addition, some tooling segments and support ribs would have to be moved carefully through the very narrow openings.

The tank openings would be less than 6 feet in diameter (see Figure 2, page 24), considering that tooling segments would still be in place at that point of the disassembly process. Thus, the ability to carry out specific, delicate maneuvers to facilitate the removal of complex geometry segments and ribs from the interior finished shell was paramount. The most distant segments would be removed from the tank opening starting with the uppermost keystone segments.

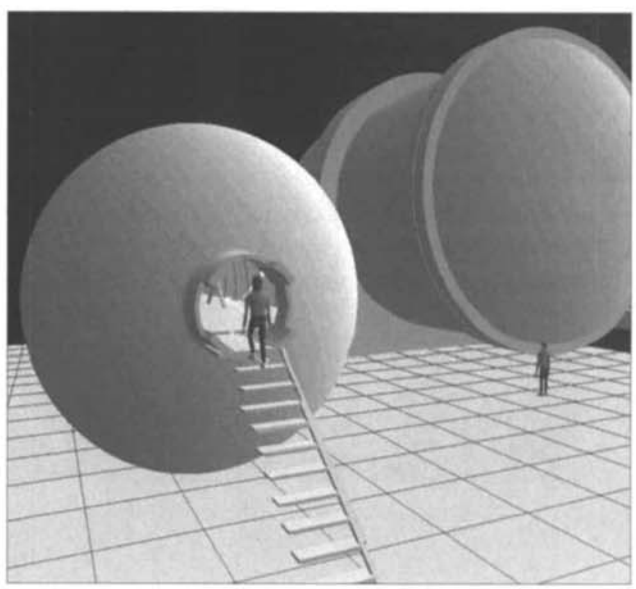

Figure 3: Tooling entrance with stairs.

Our high-level 3-D simulation also pinpointed the necessity for internal support for the composite shell as the tooling segments were removed. This support would also need to be designed modularly for rapid installation and removal. The modular function would allow supports to be added and removed with minimal effort while still providing proper internal support to prevent the composite structure from collapsing from its own weight. Also, we envisioned that external support would be required to bear the weight of the tank shell during mandrel disassembly and storage.

SIMULATION RESULTS

Our 3-D simulation of the colossal tooling was able to solve digitally, and without expensive mockups, the human/machine interface issues we encountered. The initial concern was the disassembly simulation of the colossal tooling from the internal cavity of the finished composite shell. This process is potentially dangerous to the workers disassembling the tooling and to the composite shell. We estimated that this would involve approximately 200 tooling segments weighing an average of 2000 pounds each. First, the engineers and human engineering specialists were able to visualize the tasks to be done and the problems that needed to be solved to make the design workable. A CAD model of the mandrel tool then was generated.

The model was composed of movable segments representing the actual mandrel tool segments. In addition, the need for various ancillary items became readily apparent from the graphic simulation. These pieces of equipment and material-handling devices included portable stairs or a hydraulic lift to allow workers access to the tooling opening. Figure 3 (see page 25) illustrates the enormity of the composite tank mandrel tooling and the autoclave model that was used to cure the composite tank.

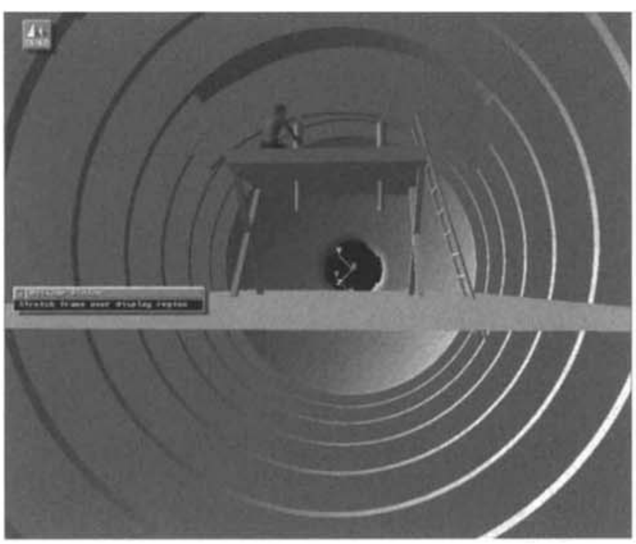

Figure 4: Interior tooling overview showing rib removal.

Workers would need support equipment and tooling to safely disassemble the 2000-pound tooling segments, move them to the centerline of the tank for transport through the tank and through the narrow exit, and access and remove the tooling segments. Adjustable modular platforms that safely support the removal equipment and workers would need to be built and systematically removed as the disassembly process advanced toward the shell opening (see Figure 4).

During the simulation and analysis, support scaffolding designed for rapid assembly/disassembly was identified as necessary to provide the tank shell with internal support. Reach and visibility envelopes for the initial CAD models confirmed that the workers, with the assistance of adjustable scaffolding and material-handling equipment, would be able to carry out the disassembly tasks. Operating forces and lifting issues were of foremost concern. Because workers would have to rely on mechanical assistance to move the tooling segments, safety issues of the human/machine interfaces were of paramount importance.

The effort involved in the 3-D simulation and analysis via ERGO software paled compared with the time and costs associated with either tooling and process mockups or actual prototypes.

Other important issues that arose during the simulation included ventilation, lighting, and noise. Ventilation was an issue because of the large but still confined space and the existence of composite material outgassing. Lighting was a process and safety issue. Noise abatement was not critical because most of the equipment and material-handling devices were not noise generators. (However, if the tooling segment assembly process had required threaded fasteners, the use of pneumatic nutrunners would probably have produced excessive noise.)

The simulated work environment was built and populated with a 50th percentile female worker. In the simulation, the worker had to climb stairs to the tank opening and then walk across a temporary platform to the center of the segmented tooling. With the platform slightly below the approximate centerline, the worker would still be at least 15 feet above the bottom of the shell and roughly 20 feet below the uppermost tooling segments and support ribs (see Figure 5). We envisioned that various scissor-lift-type platforms would be raised to support workers during the unfastening tasks and then used to lower the removed segments to the equipment used to transport the segments from the tank shell.

Figure 5: Modular support equipment

RESULTS AND SUMMARY

The logistics and ergonomics and safety issues brought to light by this comprehensive research based on use of the ERGO software was presented to the engineering management team, which was responsible for deciding which processing direction the colossal tank production process would take. The power and visual ability of the software to graphically illustrate the overwhelming evidence revealed by the analysis convinced the managerial team that the colossal tooling methodology for manufacture of these huge tanks must be abandoned. The analysis clearly pointed out the many ergonomics and safety issues that would arise by this manufacturing method. Therefore, the decision was made to use alternative materials, such as aluminum plates rather than composites, to fabricate the tanks in a traditional method. This eliminated the need for the segmented tooling system required by composite layup process.

The reaction of the management team to the 3-D graphics presentation showing the digital worker carrying out the various disassembly steps was a clear and decisive factor in discarding the segmented tooling and composite process. The effort involved in the 3-D simulation and analysis via ERGO software paled compared with the time and costs associated with either tooling and process mockups or actual prototypes.

High-level 3-D graphics software incorporating various ergonomic analysis algorithms helped our efforts to determine if the mandrel tool assembly/disassembly process would be safe and protect the health of workers carrying out these tasks. In addition, the graphical software was extremely helpful in identifying material handling equipment and devices to aid in these processes.

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