Colossal Tooling Design:
3D Simulation for Ergonomic Analysis

Steve L. Hunter, Ph.D.
Associate Professor
Forest & Wildlife Research Center
Mississippi State University
NASA MSFC ED42
Human Factors Specialist
shunter@CFR.MsState.edu

Robert E. Thomas, Ph.D.
Associate Professor
Industrial & Systems Engrg. Dept.
Auburn University

Charles Dischinger
NASA
Marshall Space Flight Ctr.
ED42 Lead

Majid Babai
NASA
Marshall Space Flight Ctr.
ED34 Lead

INTRODUCTION

In manufacturing, ergonomics and human factors issues must be considered during the design and utilization phases. These applied human factors concerns include but are not limited to, reach ability, visibility, lift factors, kilocalorie usage, repetitive motion, ventilation, lighting, and many more. When the tool size becomes colossal, say 35 feet or more in diameter and 90 feet or more in length; and the tool weights an estimated 200 tons, these normal human engineering factors become critical to the safety and health of the workers (see Figure 1). Schaub, et al, (1997) stated that preventive health care is one of the basic challenges facing ergonomics.

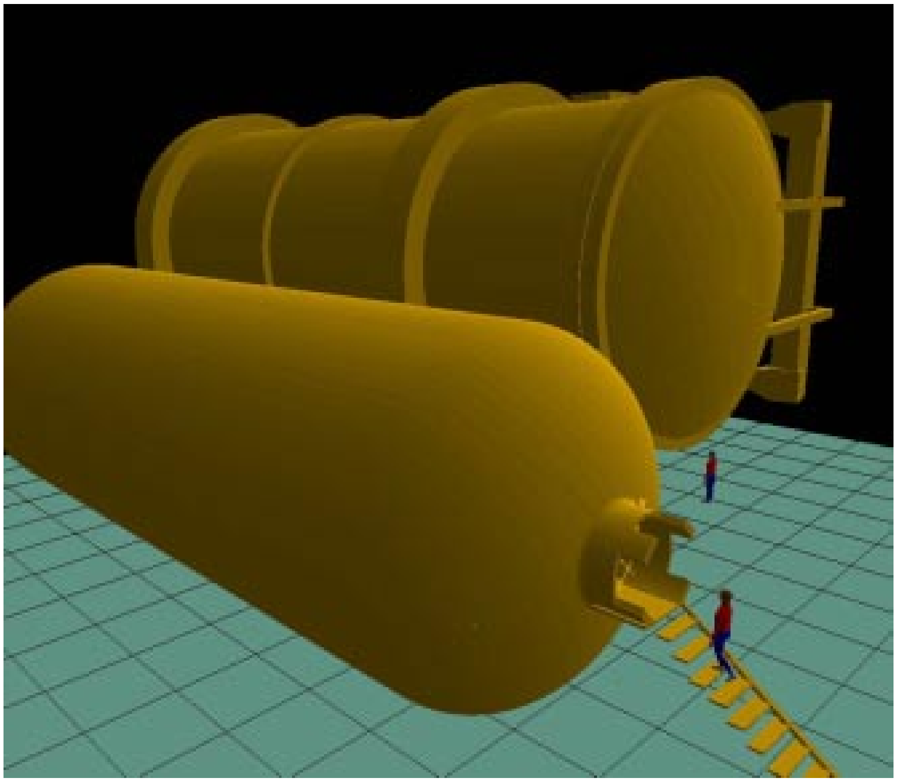

Figure 1: Colossal tooling and autoclave for composite tank lay up and cure.

These colossal mandrel tools will be used for composite lay up for the fabrication of aerospace related fuel tanks. It is no small task to manually disassemble the fully assembled tool that is surrounded by the finished composite shell; especially, when the mandrel tooling is composed of individual segments that may weight up to 2,400 pounds. In addition, the tool segments removal must be completed not only extremely carefully to protect workers carrying out the tool disassembly tanks but also to protect the thin, relatively fragile finished composite shell surrounding the tooling. Diehl et al (1997) relates how 3D simulation was originally developed partly due to the large expense and dangers of designing and testing complex systems. Compounding the problem, this disassembly effort is to be completed in a confined space that may contain material out gassing, poor ventilation, poor lighting, while carried out with the aid of large, bulky material handling equipment. The disassembled tooling segments must be removed from the composite shell through an opening less than six feet in diameter. The shear enormity of the tooling assembly and, especially, the disassembly operation takes human engineering in manufacturing system design to new vistas.

As early as 1995, Nayar warned the manufacturing world that we should not ignore the use of high level computer generated graphical ergonomics and human factors engineering during the product and tool design stages. This is especially true when designing very large tooling. Three-dimensional simulation to assist decision-making during the tooling design phase is extremely important and cost effective. The design and human factors engineers have opportunities to visualize and carry out various mechanical and ergonomic analyses along with what if scenarios. The list of ergonomic and human engineering tools in the Delmia ENVISION ERGO software package, used for this simulation, can be used to accomplish analyses that can provide detailed information on load and stress situations, which may effect the executability and tolerability of work situations (Schaub et al, 1997). The analysis and information gathering is 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 while saving the organization the time and expense of physical mockups.

LITERATURE REVIEW

Research regarding utilization of 3D or virtual Reality (VR) simulation for the design and ergonomic analysis of extremely large tooling for composite lay up appears minimal. Several papers illustrate the use of computer simulation for testing of composite laminates. Krueger and O Brien (2001) described a shell/3D modeling technique development using a 3D solid finite element model for testing composite de-lamination. Aono et al (1994) reported that 3D simulation has been used as a modeling and optimization tool to fit composite woven fiber to curved surfaces. Aono did not mention the use of 3D simulation for tool design or human engineering analysis. Sundin (2001) describes participatory ergonomics using 3D computerized simulation as a means for improvements in 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) relates how 3D simulation was developed partly because of the expense and hazards of testing and evaluation of complex engineering projects. Diehl did not report any utilization of computerized 3D or VR simulation for modeling or human factors evaluation nor analysis of large tooling in manufacturing. 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.

3D SIMULATION SOFTWARE TOOLS

According to ergonomics professionals, integrating knowledge gathered from human engineering research as early as possible in the design of a product or system, thus reaping the most benefit for the least outlay of funds, is an ultimate objective (Feyen et al, 1999). Several software programs are commercially available that are capable of carrying out reliable ergonomic analysis. The software 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 utilized with anthropometrically correct computer-generated digital humans. This sophisticated tool was central to the ergonomic analysis reported in this research.

COMPOSITE SHELL MANUFACTURING

The manufacturing sequence for a cylindrical tank is accomplished by wrapping composite material, in thin alternating layers, around a spinning mandrel of proper geometry. The mandrel may be manufactured from various materials; however it must have strength to withstand the composite laminate wrap crush forces while withstanding the curing temperatures of the autoclave. After wrapping, the composite covered mandrel must be autoclaved for composite curing. However, the mandrel designs must provide for ease of removal of the forming mandrel after the composite/resin application and curing cycle has been completed. Further, in the case of huge fuel tanks, the mandrel tool may have additional composite layers added. Thus, after each wrapping cycle the composites must be autoclaved for curing. After final curing, the mandrel tool and the composite shell must be carefully separated.

Core removal can be accomplished by several methods. Typically, the mandrel is collapsed, washed out if disposable material is used, melted out if eutectic material is utilized, or disassembled in 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 longitudinal interlocking tooling segments. The total assembled segments represent the complete internal tooling mandrel for the composite shell.

For longitudinal 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 designing a disassembly operation that puts workers at heights up to four stories. Couple this working height with tool segments weighting up to 2,400 pounds, thus the disassembly requires specially designed material handling equipment. One must keep in mind that the tooling segments are removed beginning at the 12 o clock position with the keystone-tooling segment being removed first. The upper most segments can be lowered almost vertically to the tank horizontal centerline. However, 3D simulation immediately pointed out that as subsequent segments are removed they are displaced further away from the vertical position. The removal path becomes more horizontal as the disassembly process proceeds toward the nine o clock and three o clock positions. This situation forces the removal equipment to increasingly cope with segment removal from a horizontal position rather than from a vertical position. The opposite situation occurs as the workers pass the nine o clock and three o clock positions. Ultimately, the processes progresses to segments located at the six 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.

3D simulation, when used to analyze the above situation, clearly pointed out the need for special tooling segment removal equipment and material-handling devices. It became readily apparent that these devices would be critical to the success of this manufacturing process. The removal equipment should be divided into two categories. The first category would be equipment and material-handling devices to disassemble and transport tooling segments to the tank centerline. The second category of equipment would include machinery and material handling equipment for transporting tooling segments from the composite tank centerline and outside to a storage or assembly area adjacent to the tank. This is 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 will have to be moved carefully through the very narrow openings.

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

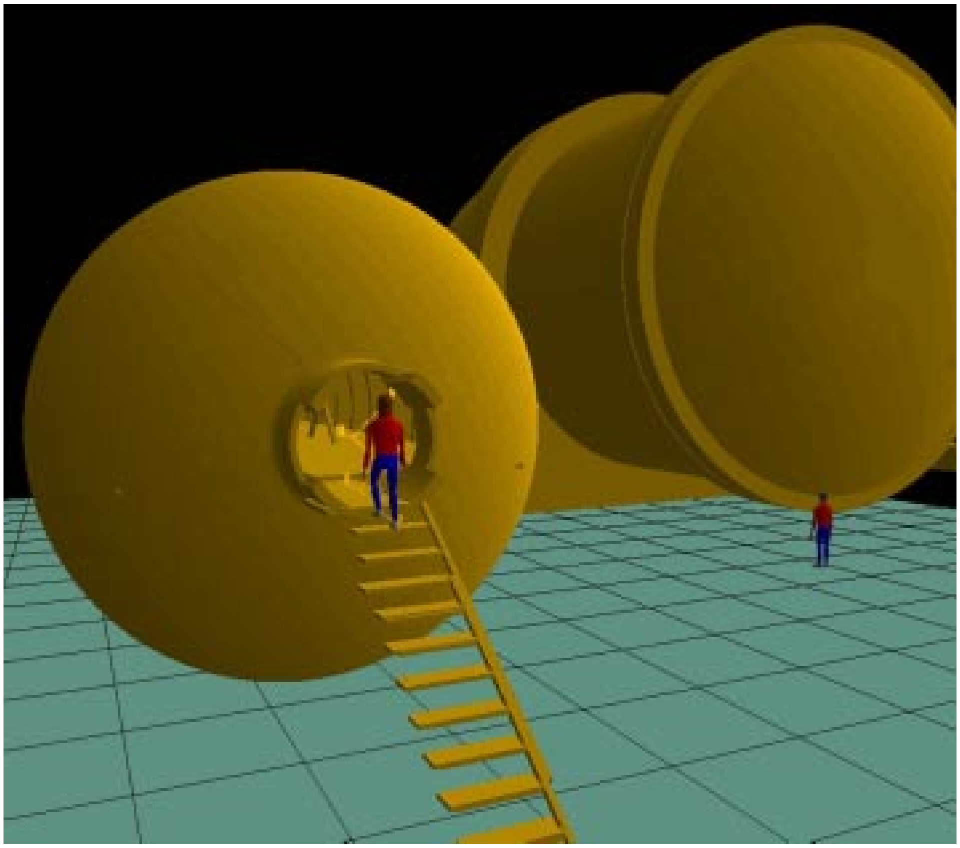

Figure 2: Simulated female worker entering tooling opening.

The high level 3D simulation also pinpointed the necessity of internal support for the composite shell as the tooling segments are 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 worker effort while still providing proper internal support to prevent the composite structure from collapsing from its own weight. Also, it was envisioned that external support will be required to provide support of the tank shell during mandrel disassembly and storage.

SIMULATION RESULTS

The 3D simulation of the colossal tooling was found able to solve, digitally and without expensive mock-ups, man/machine interface issues. 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, which was the designed purpose for the tank shell tooling. It was estimated that this would involve approximately 200 tooling segments weighting an average of 2,000 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 addressed and 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 to the mandrel tool, 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 man lift to allow workers access to the tooling opening. Figure three illustrates the enormity of the composite tank mandrel tooling and the autoclave model that will be used to cure the composite tank.

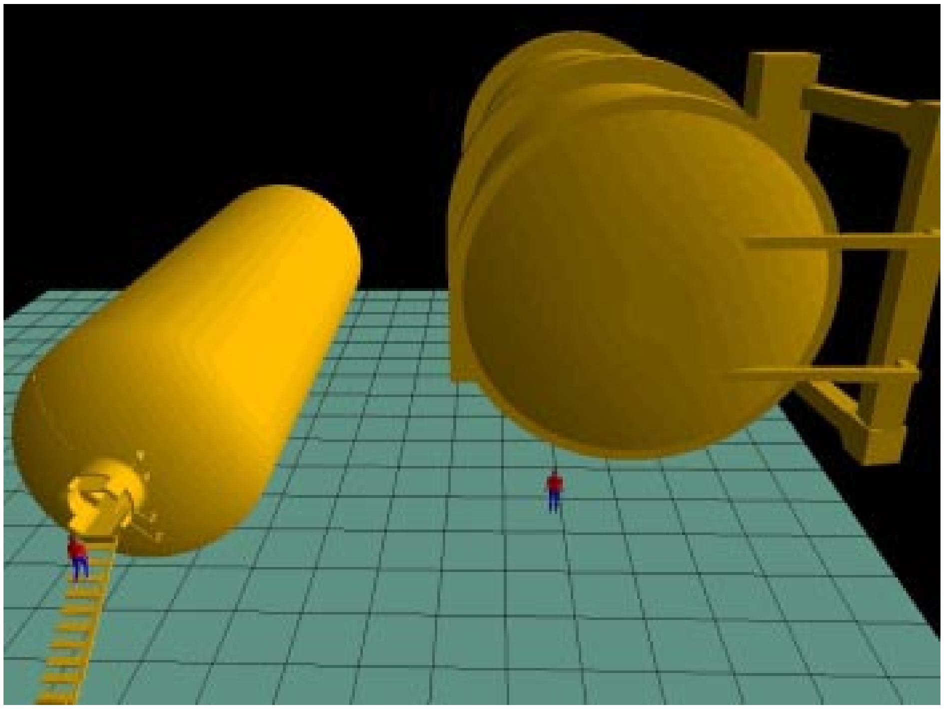

Figure 3: Colossal tool and autoclave used for composite tank fabrication.

The first challenge that was readily apparent was the magnitude of the effort needed to safely disassembling 2,000 pound tooling segments. The segments then had to be moved to the center line of the cylinder-shaped tank in order to transport them transversely through the tooling tank shell and through a narrow diameter exit. The workers would also need support equipment and tooling to 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 advances toward the shell opening (see Figure 4). Support scaffolding, designed for rapid assembly/disassembly was identified, during the simulation and analysis, 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 considering the size and weight of the tooling segments. Since it is impossible for a worker to physically move any of the tooling segments without mechanical assistance, the primary concerned was safety issues of the man/machine interfaces.

Figure 4: Assembly and disassembly tooling

Other important issues that arose during the human worker and mandrel tooling disassembly simulation included ventilation, lighting, and noise. Ventilation was of primary concern because of the large but still confined space and the fact of composite material out gassing. Lighting was a process and safety issue. Noise abatement was not critical since most of the equipment and material handling devices were not noise generators. However, if the design of tooling segment assembly utilized threaded fasteners then the use of pneumatic nutrunners are possible excessive noise producers.

The simulated work environment was built and populated with a 50 percentile female worker. The simulated environment and workers were to scale. The simulation had the worker climb stairs to the tank opening and then walks 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 upper most tooling segments and support ribs (see Figure 5). It is envisioned that various scissor lift type platforms will be raised to support workers during the unfastening tasks and then utilized to lower the removed segments to the removal equipment used to transport the segments from the tank shell.

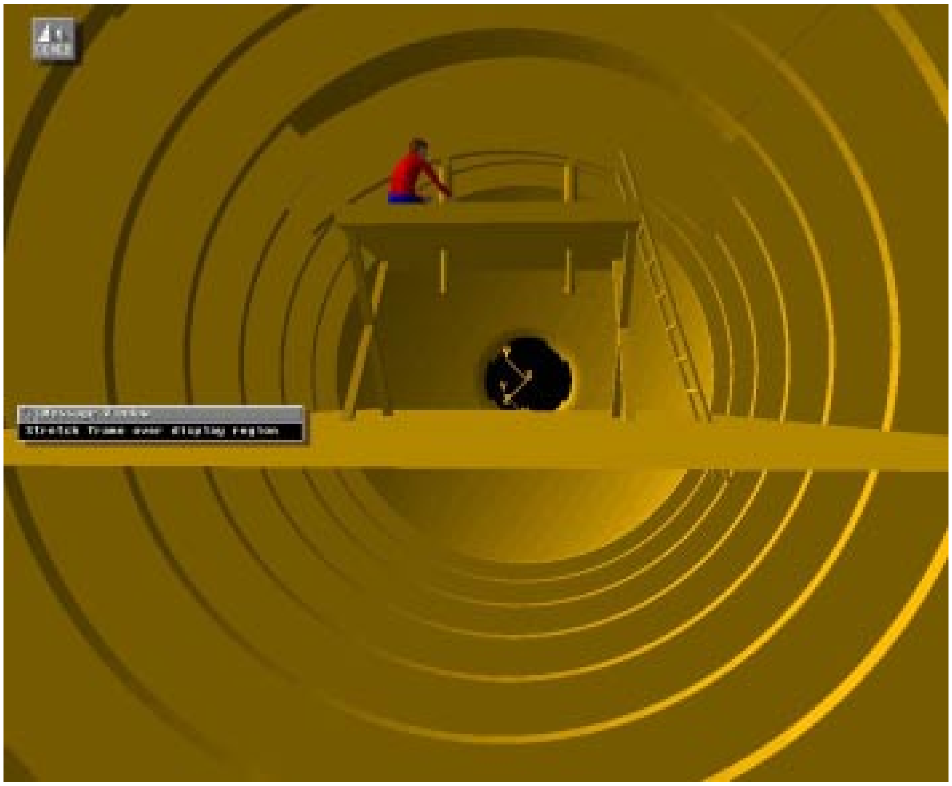

Figure 5: Equipment platform

SUMMARY

The application of high-level 3D simulation software to the design phase of colossal mandrel tooling for composite aerospace fuel tanks was accomplished to discover and resolve safety and human engineering problems. The analyses were conducted to determine safety, ergonomic and human engineering aspects of the disassembly process of the fuel tank composite shell mandrel. Three-dimensional graphics high-level software, incorporating various ergonomic analysis algorithms, was utilized to determine if the process was within safety and health boundaries for the workers carrying out these tasks. In addition, the graphical software was extremely helpful in the identification of material handling equipment and devices for the mandrel tooling assembly/disassembly process.

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