

## Recent Architectural Engineering Projects Using Rapid Prototyping

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### Abstract

In today's construction industry, with the introduction of new materials, free-form shapes of buildings, special problems with historical preservation, LEED Certification of buildings and even buildings with very large components that move, there are many new challenges for architectural engineers. This paper highlights some of the work done at Milwaukee School of Engineering by undergraduate students in summer of 2002 and 2003 that links architectural engineering with our Rapid Prototyping Center. This work started as research under the *Research Experience for Undergraduates (REU) in Solid Freeform Fabrication* program at MSOE. This is a program sponsored by the National Science Foundation. In the past projects have ranged from replication of historical decorative plaster details, writing code to translate drawing files into a form that can be read by the rapid prototyping machines, to modeling a building designed for Milwaukee School of Engineering by Santiago Calatrava. More recent projects have explored the use of Visual Basic to translate drawings into a form that can be utilized by rapid prototyping (RP), a method of using RP and photo stress analysis in the design of point supported glass, and two projects that utilize GIS data and RP to study the Milwaukee River Watershed. An encouraging side benefit of this undergraduate research has been a high percentage of our REU students going on to graduate school.

### I. Introduction

#### Milwaukee School of Engineering

Milwaukee School of Engineering (MSOE) is a private, coeducational nonsectarian university located in a metropolitan center. It provides a balanced education -- undergraduate and graduate -- for men and women in the disciplines of engineering, engineering technology, business, communication, construction management, medical informatics, nursing and perfusion (<http://www.msoe.edu/president/mission.shtml>). The mission is accomplished through an organized environment that places carefully recruited students among highly qualified faculty, a dedicated support staff and strategic partners in business and industry - all committed to meeting the ultimate objective of a graduate fully prepared for immediate productivity and advancement.

### II. REU Program and Rapid Prototyping

The REU program at MSOE is funded by the National Science foundation and provides undergraduate students an opportunity to gain hands on experience in doing research. Topics of research at MSOE include biomedical, bio-molecular, aerospace, architecture,

manufacturing and electronics. Students are paired with a faculty advisor and explore their topics through research, field trips, group problem solving sessions and presentations. All research projects are connected in that they all deal with some aspect of rapid prototyping.

The Rapid Prototyping Center at MSOE has equipment representing the four major technologies of rapid prototyping used today. Stereolithography (SLA) uses a UV laser to create a part in a vat of light sensitive liquid photo-polymer, one layer at a time. Laminated Object Manufacturing (LOM) uses a laser to build successive cross sections of a part out of paper. Fused Deposition Modeling (FDM) creates successive cross sections of a model by depositing small beads of ABS plastic. Selective Laser Sintering (SLS) creates layers of a 3D object by fusing (sintering) plastic or metal powder layer by layer.

Having the REU program at MSOE has been beneficial to the Architectural Engineering and Building Construction Department. Research projects have been on display and student presentations have been well attended by other students. This increased awareness has translated into increased use of laser cutters and RP machines which has improved the quality of the architectural engineering capstone design projects at MSOE. The Architectural Engineering and Building Construction Department at MSOE has been known in the past for producing solid graduates ready for the construction industry. More recently there has been a rise in student interest in research and in graduate programs not only at MSOE but at other institutions. This paper will highlight four of the architectural engineering REU projects that have been completed in the last two years. Two of these undergraduate student researchers are products of MSOE and two are from other universities.

### **III. Why model architecture**

The question that comes up most often is: Why build models in the first place? The first reason that an architect may have for creating a model of a building very often is to test visually the assumptions he/she has made about a design during the design process and try alternative solutions. Although cutting mat board and foam core by hand can be tedious and time consuming modeling in 3D allows a level of exploration that cannot be achieved with 2D drawings. The added quality it brings to the design process is worth it.

One very important answer to this question is that clients like models. They like to walk around them, hold them up and view them at eye level to visualize what it might be like to stand in front of the building. We have tried a number of cad packages that allow a virtual tour of a design project. A couple of years ago one of our student design teams proposed that they build a virtual model of their project and produce a movie “walk through” for final presentation to the client. The other three design teams presented physical models of the project. The cad model, rendered with lighting and materials took about the same amount of time to build. In the end, however, the most striking comment from the client was that “It would have been nice if you would have built a model like the other teams”. A physical model is indispensable in helping to sell ideas to a client.

Another interesting area of architecture and rapid prototyping is the replication and restoration of historical ornamental detail on buildings. The potential to use rapid prototyping to create positive, the object, and negative, the mold, is well understood in the mechanical engineering field. The same process can be applied to historical details in architecture.

#### **IV. Student Research Projects**

Hong Loan T. Bui Participated in the REU program at MSOE in the summer of 2002. Bui's project was a continuation of some earlier projects at MSOE that looked at translating AutoCAD drawings into a format that could be interpreted by rapid prototyping (RP) machines. A common problem with AutoCAD drawings produced by architects is they use many drawing entities that cannot be read by RP machines. For example, 3D faces can be rendered in AutoCAD but since they have a dimension in the "Z" direction of zero they cannot be built. There are many drawings in archives that make extensive use of 3D Faces and even though they look like a solid object on a computer screen, they cannot be translated directly into the required "stl" format for rapid prototyping.

The challenge for Bui was to find a sample drawing that represented a common drawing type that could not be built in the MSOE Rapid Prototyping Center, and find a way to translate it into a more compatible form. In the past some of our participants experimented with AutoLISP, an artificial intelligence program that comes with AutoCAD. One drawback with AutoLISP programming is that it is an un-compiled program and it can be very slow. Built in error checking is primitive and at times tedious for all but experienced programmers. Although Visual Basic has been around for a while, it is relatively new to AutoCAD users. After looking at all of the options, Bui chose to write in Visual Basic.

Bui chose a cad file of a human face made up of approximately 1200 triangle shaped 3D faces to test the program. Although many technics were tried, the most successful turned out to be the extrusion of the 3D Faces in the direction of the "normals". That is perpendicular to the face of the plane. Because in most drawings of this type, Bui found that the positive and negative direction of the normals seldom was consistent with the inside and outside of the model, Bui's first attempts yielded models that had faces that randomly projected forward. This was not the smooth surface that was expected. After more trials Bui found that a thin shell structure could be created by extruding a very small increment in the positive and negative direction of the normals. Although making the structure thicker could spoil some of the fine detail of a surface in most cases the increment is so small as to be unnoticed in the final model. Another problem that is noticeable was a "V" shaped void that is left when the dihedral angle between two planes is greater than 180 degrees. This problem was fixed by using a program first developed by Koharian and then improved upon by Brown. Koharian and Brown's program takes any selection set of lines in a drawing and extrudes them, one at a time, into a solid of any cross section using the end points as the starting and ending points of the extrusion. In this case Bui created cylinders on all of the edges of the 3D faces with a diameter that matches the final thickness of the extrusion. This effectively filled in all of

the “V” shaped voids when all of the extrusions were joined together.

Bui presented a paper at the National Conference for Undergraduate Research (NCUR) in spring of 2003. Bui is currently finishing her undergraduate degree at University of Texas at Austin and plans for graduate school are not known at this time. Figure 1 shows the SLA part and Figure 2 shows the cad file used to create the part.



Figure 1

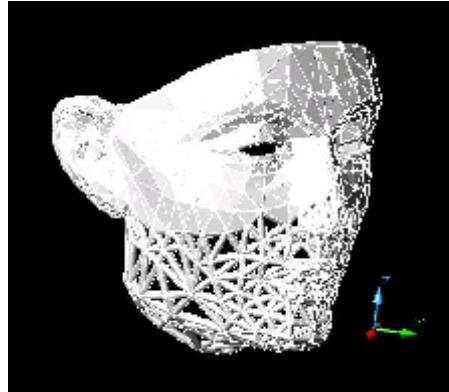


Figure 2

John Knowles participated in the MSOE REU program in the summer of 2002. Knowles’ research project was also a continuation of earlier work done in the REU program. Knowles’ research looks at modeling architectural components of buildings using stereo lithography and then testing those parts structurally using photo stress analysis. The goal of this research was to verify the accuracy of photo stress analysis by comparing the test results of an RP prototype with an FEA analysis and an actual steel part. Specifically Knowles built a prototype of a spider connection used for point supported glass wall systems. Interviews with engineers who design such systems revealed that in almost all failures the glass is the component that fails. Not much is known about the stainless steel “spiders” that hold the glass other than they are probably over designed.

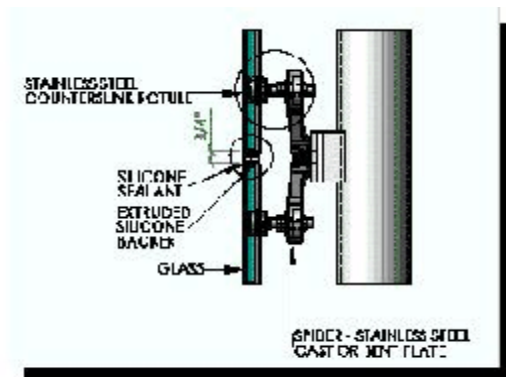
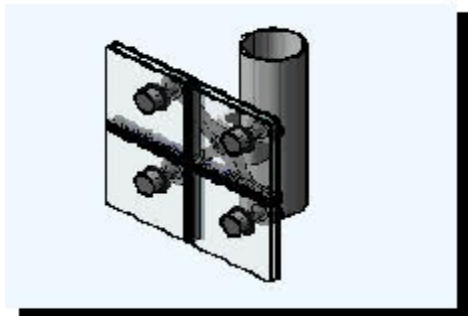


Figure 3

Figure 3 shows a typical spider connection and how it holds the glass. An interesting observation about parts made using stereo lithography is that because of the layered

method of fabrication a part will have a slight internal grain that shows up when using photo stress analysis that must be taken into account. In other words the orientation of the part on the build platform makes no difference in the appearance of the part, but it can make a difference in the test results when using photo stress analysis. Clearly more needs to be done in this area. To overcome this “grain” in the structure the part first needed to be covered with a reflective paint and then covered with a clear coat that will react to the polarized light when stress is applied.. Knowles is demonstrating the application of this clear finish in figure 4. Figure 5 is an example from the Stress Photonics, inc. website that shows the resulting stress patterns on a wrench as force is applied.



Figure 4

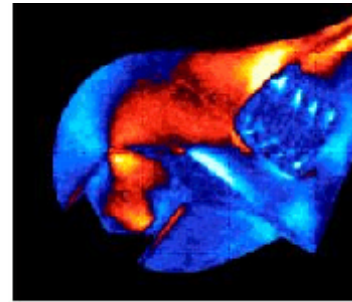


Figure 5

Knowles presented his findings at the National Conference for Undergraduate Research (NCUR) in spring of 2003. Knowles is currently working towards a masters degree in structures from MSOE.

Nicole Pederson participated on the REU program at MSOE in the summer of 2003. Pederson’s topic is concerned with the effect cities have on natural watershed areas. This project is the result of collaboration between the Milwaukee Metropolitan Sewerage District (MMSD) and the REU program. MMSD currently funds some demonstration projects involving green roof systems in the city of Milwaukee. Since models can be an important tool in educating the public, Pedersen approached MMSD about using RP modeling to demonstrate the virtues of green roofed buildings. The sewerage district in Milwaukee is especially interested in promoting green roofs not only because it is a more responsible use of resources, but because the city of Milwaukee has a combined storm and sanitary sewer system in much of the district. Heavy rains can easily overload this system and the deep tunnel reservoir that was built to alleviate the problem. When the system is overloaded there is always a chance that untreated sewage will be released into Lake Michigan. Pedersen’s research project looks at RP modeling as a way to demonstrate in a scaled down way the impact rain has on the infrastructure of the city of Milwaukee. Rain is visually represented by water in this model and impact on the sewer system is graphically represented by depth of water in two reservoirs at the base. One represents a green roof system and one represents the system as it exists today without green roofs. Figures 6 and 7 show details of the model produced by Pedersen. Figure 8

is a map of the entire Milwaukee River Watershed area.

Pedersen is currently working towards a masters degree at MSOE in environmental design. Pedersen's research paper has been accepted for presentation at the spring 2004 National Conference for Undergraduate Research.



Figure 6

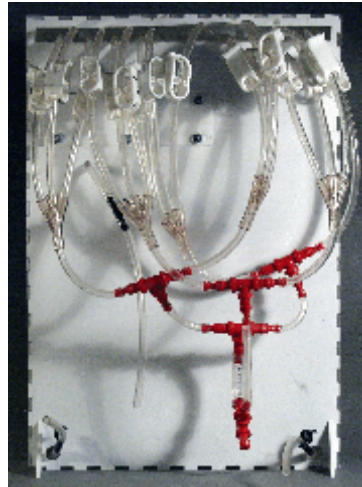


Figure 7

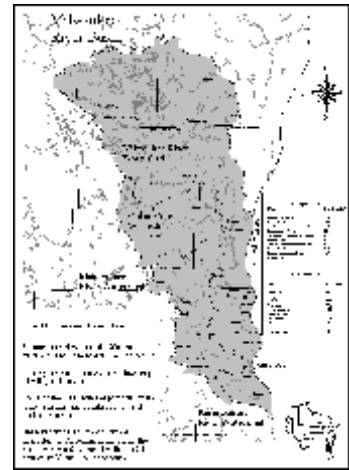


Figure 8

Laura Jacobs came to the Milwaukee School of Engineering REU Program in the summer of 2004 from Purdue University. Jacobs like Pedersen researched an aspect of watershed models. After visiting with experts from the Schlitz Audubon society and the MMSD Jacobs decided to look at the possibility of translating United States Geological Society (USGS) data directly into AutoCAD and then into an "stl" format that the RP machines can import. Specifically Jacobs looked at the digital elevation maps (DEM) that the USGS publishes. A problem that both Schlitz Audubon and MMSD identified is that it is hard to educate the public about regional watershed issues if people don't even know what watershed area they live in. This is extremely important because watershed areas do not follow municipal government lines and solutions to problems need to be worked out on a regional level. RP models could be an answer to that problem if it was possible to quickly produce models of parts or even the whole watershed areas for study and education of the public. Jacobs was successful in producing a small section of the Milwaukee River that runs through the downtown area. The model produced was scaled up in the vertical axis to enhance the finer details of water runoff.

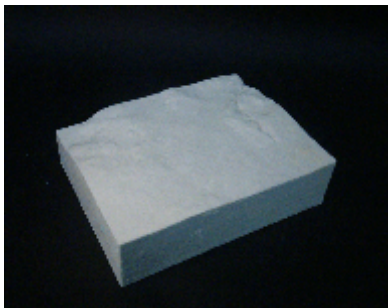


Figure 9

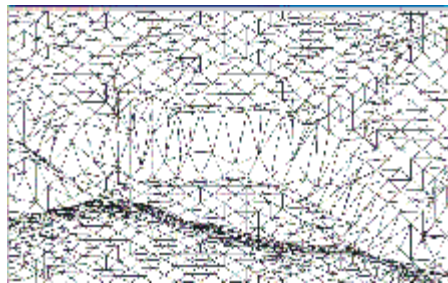


Figure 10



Figure 9 shows the model made from DEM data available from the USGS. Figure 10 shows a closeup of the cad drawing used to produce the model. Jacobs' paper has been accepted for presentation at the 2004 National Conference for Undergraduate Research. Jacobs is finishing up undergraduate work at Purdue University and indicates that graduate school will most likely be in her future.

## Conclusions

To date MSOE has had 78 students participate in its REU program. Of this number 61 students have graduated with a bachelor's degree. The others are still juniors or seniors in college. Of the 61 students that have graduated 56% have gone on to graduate school and 5 students have not kept in touch with MSOE so it is unknown at this time if they have gone on to graduate school or not.

Of this 56% (34 students):

50% are currently enrolled in Masters programs.

38% are enrolled in Ph.D. programs.

9% have completed their Masters degree.

3% have completed their Ph.D. program.

The National Science foundation mandates that students in MSOE's REU program come from many different universities so all of the students listed above are not MSOE students. Some of these students may have had a plan to go on to graduate school before participating. MSOE has not kept hard statistics in that area, but from the many informal conversations the author has had with students about plans for graduate school, doing research at the undergraduate level seems to have had a very positive affect on many to pursue a graduate degree. Seeing these research projects on display has generated much interest in research and graduate school opportunities from students in our department who have not participated in an REU program as well.

## Bibliography

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Michael McGeen is an Associate Professor in the Architectural Engineering and Building Construction Department at Milwaukee School of Engineering. He is active in the Rapid Prototyping Center at MSOE and has served as an advisor for the Research Experiences for Undergraduates program since 1998. Professor McGeen is a registered Architect with a Masters in Architecture from the University of Wisconsin - Milwaukee. In May of 2002 he was the recipient of the Milwaukee School of Engineering, Karl O. Werwath Research Award.