The Madison Group

TMG News

October 2013

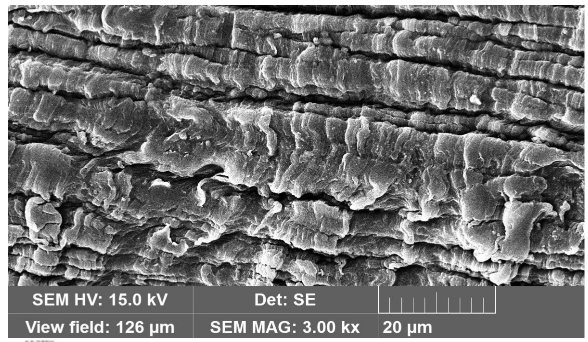
TMG News is a quarterly newsletter that is provided to clients and friends of The Madison Group. It is the goal of The Madison Group and this newsletter to assist in the dissemination of knowledge to plastics professionals. TMG News provides plastics-related articles and information regarding educational opportunities.

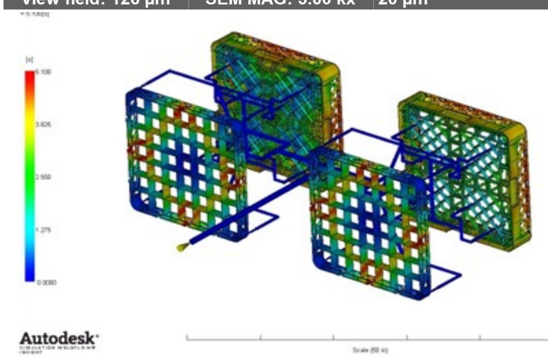
This issue of the newsletter features the third and final article dedicated to poly(vinyl chloride) (PVC), which describes common failure mechanisms of this important material. The other article addresses the importance of accounting for non-linearity in finite element analysis when validating a plastic part design.

In addition to the articles, the newsletter includes an announcement for a plastic part failure analysis course that The Madison Group will be leading. The three-day course entitled, "Plastic Part Failure: Analysis, Design, and Prevention" is offered through UW-Milwaukee School of Continuing Education, and will provide an in-depth look at failure analysis of plastics and how these failures can be prevented. The seminar will be held in Milwaukee, WI from December 2-4, 2013.

On a final note, The Madison Group celebrated its twentieth year in business this August. It has been a great journey watching the company evolve into its current state. We would like to thank all of our clients, and friends that have made the first twenty years an enjoyable and fruitful experience. We have truly enjoyed and valued the opportunity to be a member of your team.

Jeff Jansen





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PVC Part 3: Failure

Javier Cruz, Ph.D.

PVC has very good performance characteristics that result in parts used for numerous applications. But like any other polymer it does have its limitations. Some of which, if not properly understood and accounted for, can easily lead to premature failure.

Parts I and II discussed the basics of PVC material and its processing characteristics. Today, we will present examples of typical failures that we encounter with PVC material.

A well known limitation of PVC for many applications is its temperature limit. Rigid PVC has a glass transition temperature (Tg) of 80°C. This means that the material, being amorphous, will rapidly soften when this temperature is exceeded. Even approaching the Tg can be critical for the material. PVC is used in many applications where this temperature limit could unexpectedly be exceeded. One example of this is in the hotter southern states where houses use very reflective glass for windows. The windows are designed in this manner to keep the inside of the house cooler. However, the reflection can create unexpected heat build-up against a vinyl siding on a house next door which can lead to softening, warping, and damage of the siding.

For outdoor applications, such as the one previously mentioned, other factors such as UV-radiation can also adversely affect certain grades of PVC. Even indoors UV exposure from fluorescent lamps has been shown to affect certain grades of PVC. Typically, lower exposure to UV-radiation will cause a surface aging which results in a discoloration or yellowing of the material. In many instances, although mechanical properties may not be affected, excessive color changes can be unacceptable and considered a part failure for an application. The yellowing is attributed to the formation of conjugated doubles bonds as the molecules break down. Therefore, severe continuous exposure to UV can penetrate much further causing excessive chain scission and material embrittlement. Additionally, chalking can occur as the material degrades and fillers come to the surface.

As discussed in Part I, the performance of a given PVC grade is directly dependant on its unique formulation. For example, impact modified transparent rigid PVC is known to be significantly susceptible to UV exposure. Specific pigments, thermal stabilizers, fillers and UV absorbers can aid in reducing the effects of UV aging on the material. Most of these protect PVC by preventing the formation of the conjugated double bonds, having anti-oxidative properties, and absorbing UV (i.e. taking the hit so the polymer does not). Common UV absorbers used with PVC include benzophenone and benzotriazole. Titanium Dioxide (white) pigment can also aid in UV resistance as it serves as an excellent UV-absorber. Darker fillers such as carbon black also absorb and can perform well, even considering the expected temperature rise that will occur with a darker material. Figure 1 is an example of a bottle containing a citric based cleaner that became brittle while sitting on a shelf in a garage for about three years. Here, although the PVC is known to have good chemical resistance with citric acid, the long-term exposure to UV and slight temperature rises led to degradation and a fracture at the base of the bottle. {Figure 1}.

Figure 1 - View of a fractured PVC bottle that failed in a brittle behavior due to material embrittlement from UV exposure and limited temperature rises.

Additives used with PVC for other purposes, such as to limit degradation due to thermal effects during processing, can also aid in preventing degradation from environmental effects such as UV. In the end, both mechanisms (thermal and UV) result in molecular break down and the formation of conjugated double bonds. The overall concentration and types of additives used can therefore have a great effect on the long-term part performance. If improper additives and stabilizers are used or if most of these are consumed due to aggressive processing conditions, this can adversely affect the long-term performance of a part exposed to UV and other environmental conditions. Whether it is from processing, from aggressive UV effects, or due to long-term aging, as PVC degrades the plastic becomes more and more brittle and this will be made evident by a significant loss of impact resistance. Environmental testing methods are available to relatively quantify the performance of plastics to UV-radiation and the outdoor environment. This can be done as a preventive and comparative measure. For example, a Q-UV (sunlight rain and dew) chamber is an accelerated weather tester where plastic sheets are exposed to aggressive UV-radiation together with humidity and outdoor temperature cycles. By performing this accelerated weather test followed by impact testing of the samples, one can determine the relative performance of different materials. Preventive and comparative testing of this manner can provide good insight into which would be a better material among several comparably priced options.

As with UV, environmental effects from incompatible chemicals can also result in material embrittlement and failure. Moist chlorine gas, especially at elevated temperatures can rapidly degrade PVC. This type of failure results in severe surface mud-cracking and a loss of material properties. Additionally, the micro-cracks formed on the surface result in stress concentration regions that are susceptible to further cracking under stress. Esters and ethers on the other hand, have affinity with the PVC material and rather than degrading the material result in cracks because of a lubrication effect at the molecular level. With a high enough concentration of chemical and stress, the chemical is absorbed by the polymer and reduces the inter-molecular forces that hold the polymeric molecules together. The localized absorption results in a localized softening effect, molecular disentanglement, and a slow-crack growth mode of failure. This phenomenon is commonly known as environmental stress cracking (ESC). With ESC, the cracks show a smooth morphology characterized by the localized surface modification. Micro-cracks grow in a stepwise fashion and chemical modification of the crack tip at every step-crack progression can typically be observed through microscopic analysis of the fracture.

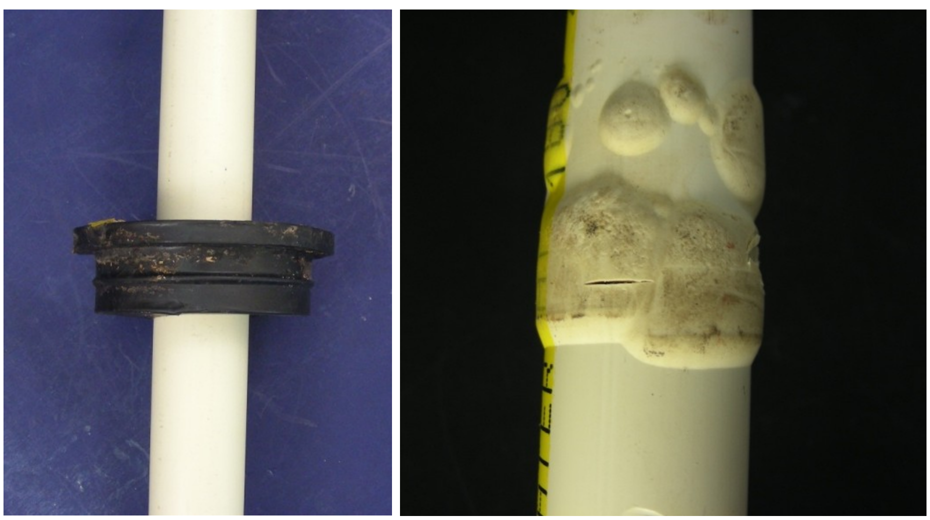

Figure 2 - Failure of a CPVC pipe due to absorption of a phthalate plasticizer from a gasket.

Certain chemicals such as phthalates have even higher affinity with PVC and can be absorbed by the polymer to the point of causing a macro-softening effect. Phthalates are actually one of the common additives used in PVC for making plasticized PVC tubes. The tubes are soft and flexible because of the plasticizing effect of the phthalate. Plasticizers interact with the polymer's molecular forces reducing them, but not to the point of solvating the polymer. Therefore, if phthalates contact rigid PVC parts, such as piping, it can result in devastating effects. An example of a failure due to migration of plasticizers into piping systems is shown in Figure 2. Here, the piping system is CPVC and not PVC. However, both perform similarly when exposed to phthalates. For the example shown, a rubber gasket was used on CPVC piping and the phthalates in the rubber migrated from the rubber to the pipe leading to softening and rupture of the pipe[1].

[1] A more in-depth discussion of this failure is discussed in the Press Release "Proset Rubber Gasket Failure" found here: http://madisongroup.com/

There are several methods that can be used as failure prevention measures during design stages to verify any incompatibilities of the material with substances that it may come in contact with. One example is a test that we commonly perform on many polymers including PVC which provides a relative measure of environmental stress cracking resistance (ASTM D 543). These types of tests are very beneficial because plastics like PVC are formulated and compounded using many different additives which can greatly affect chemical compatibility. Therefore, one PVC grade may be affected by a given chemical, while another may not. For example, Freon 11 (trichlorofluoromethane) is a chemical known to be incompatible specifically with impact modified PVC grades.

Another phenomenon that can result in failures that we observe with larger PVC parts such as large PVC piping is poor fusion which is related to poor processing conditions. A more detailed explanation of this topic was presented in part II of this series. Poor fusion is typically observed for larger parts because these are harder to process effectively. Proper processing of PVC requires enough shear and heat to effectively melt and fuse the PVC particulates that are inherent to the polymerization process. However, excessive shear can degrade the plastic. Figure 3 shows a large pipe used for underground water transport applications. These extruded pipes have a thick wall which will result in more difficult processing. The pipe shown here cracked without ever being in service. Cracking resulted from a combination of internal residual stresses from manufacturing and severely poor fusion. A proper review of the process combined with testing of the pipes for proper fusion and mechanical performance could have prevented such failures. Testing methods such as ASTM D 2152 acetone immersion test (AT) and ISO 9852 dichloromethane test (DCMT) are qualitative tests that can be performed to evaluate fusion of PVC. Additionally, ISO 18373-2, a more quantitative technique that uses DSC to evaluate the degree of fusion of PVC material has been shown to be extremely valuable for many of our failure analysis investigations.

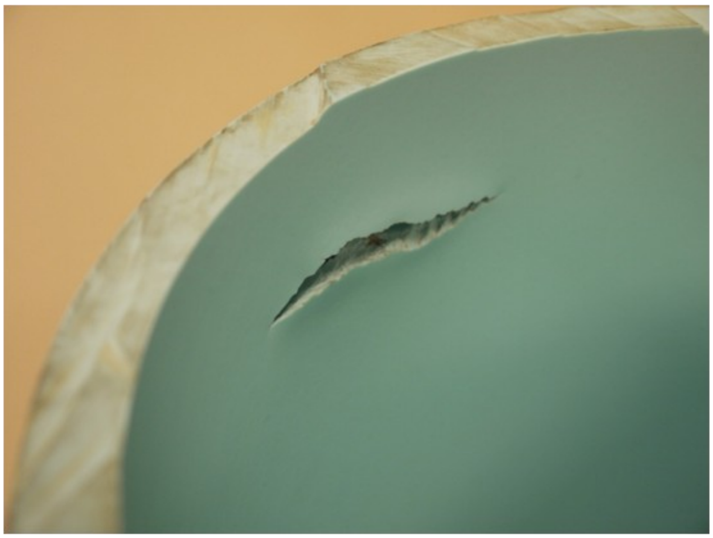

Figure 3 - View of a PVC pipe that failed without ever being in service.

As with other plastics, there are numerous reasons that can cause PVC parts to fail. Due to time constraints, I have limited this article to simply provide some quick examples of several common failure modes that we observe. However, it is important to remember that failures can be subdivided into five basic categories: material, design, manufacturing, environment, and end use. To this point, I have briefly covered three of the five categories. Design and end use are both extremely important and may be covered as individual future articles. Typical design-related failures for PVC parts are generally related to high stress concentrations due to sharp geometric transitions as well as high stresses from snap-fit assemblies. Additionally, problems due to improper mold and/or gate runner designs are also sometimes observed. End use failures refer to abuse during use or installation issues. These types of failures are also common and are typically the result of a lack of understanding of the behavior of plastics when under stress. A large percentage of these end use failures we observe show modes of failure related to creep rupture. Proper understanding of the design and stress limitations for the material can typically prevent these modes of failure. Furthermore, for stress related failures, testing techniques are available that can provide insight into the short and long-term mechanical performance of the material.

If you would like more information regarding failure analysis, materials engineering, or other plastics issues, please contact The Madison Group at 608-231-1907, or email at javier@madisongroup.com.

For further information regarding PVC read the following papers authored by the staff at The Madison Group (click on the link to access the document).

PVC Part 1: It's All About Composition

PVC Part 2: Processing

Fractographic Characterization of Pipe and Tubing Failures

The Madison Group ANTEC Papers

Engineers from The Madison Group presented three papers at ANTEC 2013, the Annual Technical Conference of the Society of Plastics Engineers.

The Role of Multiple Factor Concurrency and Statistical Distribution in Plastic Part Failure
Jeffrey A. Jansen and Antoine Rios, Ph.D., The Madison Group
When a plastic part fails, a tough question is often asked, "Why are a limited number of parts failing?". This is particularly true with seemingly random failures at significant, but low, failure rates. Two aspects are generally linked to such low failure rates, multiple factor concurrency and the statistical nature of plastic failures. Failure often only takes place when two or more factors take effect concurrently. Absent one of these factors, failure will not occur. Plastic resins and the associated forming processes produce parts with a statistical distribution of performance properties, such as strength and ductility. Likewise, environmental conditions, including stress and temperature, to which the resin is exposed through its life cycle is also a statistical distribution. Failure occurs when a portion of the distribution of stress on the parts exceeds a portion of the distribution of strength of the parts. This paper will review how the combination of multiple factor concurrency and the inherent statistical nature of plastic materials can result in seemingly random failures.

Effects of Biodiesel on Plastics
David Grewell, Tong Wang, Melissa Montalbo-Lomboy, Linxing Yao, Iowa State University,
Paul Gramann, Ph.D and Javier Cruz, Ph.D., The Madison Group
Many chemicals have the ability to attack plastics leading to failure. In some cases, the source of the chemical is not well defined. In this study, the effect of biodiesel, a fatty acid methyl ester, on various plastics, namely polyamide 6 (PA 6), polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS) and ABS/PC plastic blends was studied. Various feedstocks of biodiesel were also studied, including, soy bean oil (new and used), animal fat (tallow), corn oil as well as choice white grease. The plastics samples were tested following an ASTM standard where a predefined strain is applied to the samples prior to exposure to the solvent (biodiesel).

Effects of Glycerin Antifreeze on CPVC
Paul J. Gramann, Ph.D., and Javier C. Cruz, Ph.D., The Madison Group
David Grewell, Ph.D, Melissa Montablo-Lomboy,Ph.D, and Tong Wang, Ph.D., Iowa State University
There are multiple applications where chlorinated poly(vinyl chloride) (CPVC) may come in contact with glycerin. One common application is in fire suppression systems that could be subjected to subfreezing temperatures. Chlorinated poly(vinyl chloride) is increasingly being used for these systems in place of metal because of its many advantages, including the ease of installation, weight reduction, cost benefits and chemical resistance. When CPVC piping is used in an area that has the potential to freeze, an antifreeze solution must be used in the fire suppression systems to suppress the freezing temperature of the water and reduce possibility of failure of the piping system. Glycerin is a commonly used antifreeze for this application. The following article discusses the effects of using glycerin with CPVC piping and presents a case study of the use of bio-derived glycerin as an antifreeze agent. In general, it was found that glycerin from the bio-diesel industry had adverse effects on the CPVC.

Accounting for Non-linearity in Plastic Part Design Validation Erik Foltz

The ability to virtually validate a plastic part design has become an important tool for designers and manufacturers to develop quality new products while meeting the continually compressed time-to-market deadlines. The use of structural finite element analysis (FEA) early in the design stage allows an engineer to make intelligent decisions regarding nominal wall thickness, stiffening rib placement, and material selection. Additionally, the integration of many structural FEA packages into traditional CAD packages has exposed this tool to a much wider audience. However, to fully realize the potential of this powerful tool careful consideration of the inputs for the simulation need to be made (Remember Garbage In - Garbage Out). One important decision that needs to be made is if a non-linear analysis needs to be performed. Deciding to run a non-linear analysis can significantly increase the accuracy of a simulation, but often takes significantly more time for the computer to provide a solution. So when should an engineer perform a non-linear analysis?

Material Non-Linearity

When most engineers and designers learn about material behavior they are taught that the stiffness of the material can be characterized by a single value - Young's Modulus. The concept of Young's Modulus is that the response of a material is proportional to the load. Under this assumption, if a cantilevered beam deflected 0.125" when a 10 pound load is applied, then the beam would deflect 0.250" if the load was increased to 20 pounds. While Young's Modulus makes it easier to characterize the behavior of a material, it also over-simplifies it. In reality all materials are inherently non-linear, as it is not possible to characterize a material by a single value for all load types and conditions. Young's Modulus becomes particularly problematic when characterizing the behavior of polymers. In general polymers only exhibit a very small linear region with most resins deviating from this behavior with strains less than 1%.

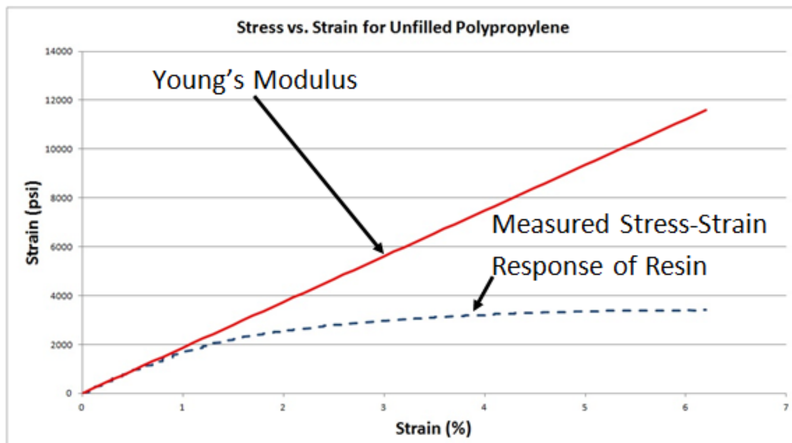

Figure 1: Characterizing the stiffness of a plastic resin by using Young's Modulus (i.e. linear assumption) can lead to an over-prediction in stress and stiffness of the part.

The point at which the material behavior deviates from the linear behavior is referred to as the proportional limit. The danger with using Young's Modulus beyond the proportional limit of the material is that the predicted stiffness of the designed part and the predicted stress in the part will be over predicted (Figure 1). Over predicting these two design parameters can lead to over-designing the part and minimize the benefit of using plastics in the first place. To avoid this material characterization over-sight the designer and analyst should look at the stress-strain behavior of the polymer and determine if the Young's Modulus accurately portrays the material response over the strain range of interest. If it is determined that Young's Modulus does not accurately predict the behavior of the resin then a more accurate model should be used. Many more refined models have been developed that better predict the behavior of polymers. Most commercial software even allows users to import stress-strain data into the program to account for any non-linearity.

Geometric Non-Linearity

Another source of non-linearity is a result of changing geometric cross-sections as a result of the loading. Geometric non-linearity takes into account the fact that the geometry cross-section can change as a result of large deformations (i.e. large displacements, large rotations, large strains). A linear analysis assumes that the stiffness of a part stays constant regardless of deflection. If the deflections of the part remain small relative to the overall dimensions of the part it is reasonable to assume that the change in the geometry has a relatively insignificant effect on the overall response of the part. However, as the deflection of the part increases the resulting geometric change in the part can yield either a stiffer or more compliant structure (Figure 2). It is generally accepted that if the rotation of the part remains less than 10-15 degrees and the deflection of the part is significantly less than the overall dimensions of the part then a linear analysis will yield reliable results. However, if an initial linear analysis results in large deformations and rotations than the analysis should be converted to non-linear to account for the modified stiffness of the part.

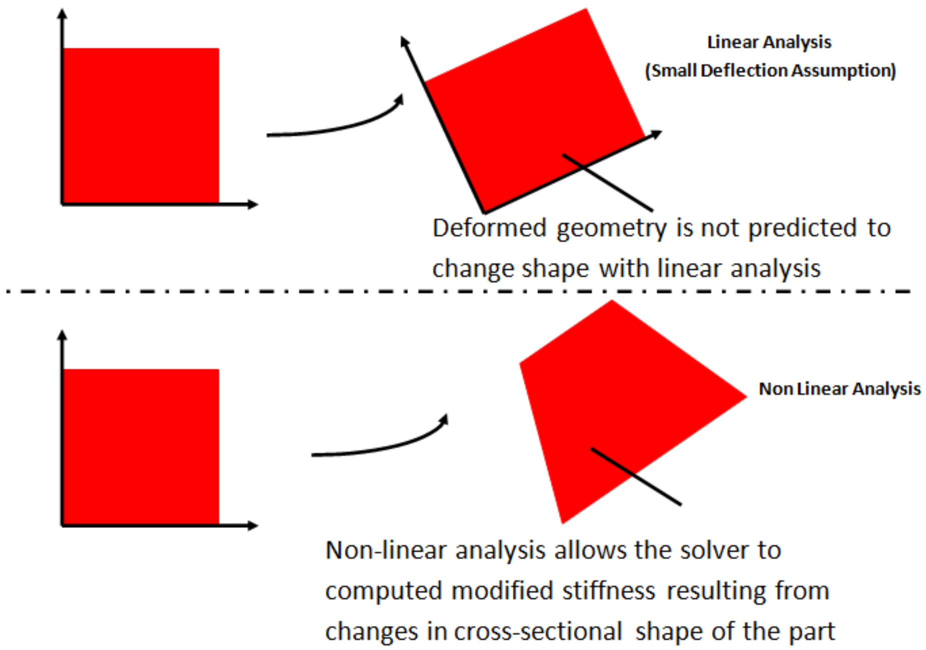

Figure 2: When parts experience large deflections and rotations the cross-section of the geometry can change, which can alter the cross section of the part. Only a non-linear analysis can capture the geometry change of the part and resulting change in stiffness.

Boundary Non-Linearity (Contact)

Boundary non-linearity arises when the boundary conditions in a FEA model change during the analysis. It is particularity prevalent when modeling contact between mating components, or during impact simulations. When modeling contact between mating components the solver has to constantly calculate and monitor how large of a contact area is generated with the applied loads. The contact area is calculated by determining how many nodes in each body are within a specified tolerance. If two nodes, on separate bodies, are within the prescribed tolerance the contact is considered closed, and a reaction force is applied to the nodes to prevent them from penetrating further through each other. If the nodes remain outside the specified tolerance the contact is considered open and no reaction force is applied. As the contact area between the mating components changes the force transfer between the two components changes, which alters the stress distribution at the interface. In a linear analysis, the solver assumes the

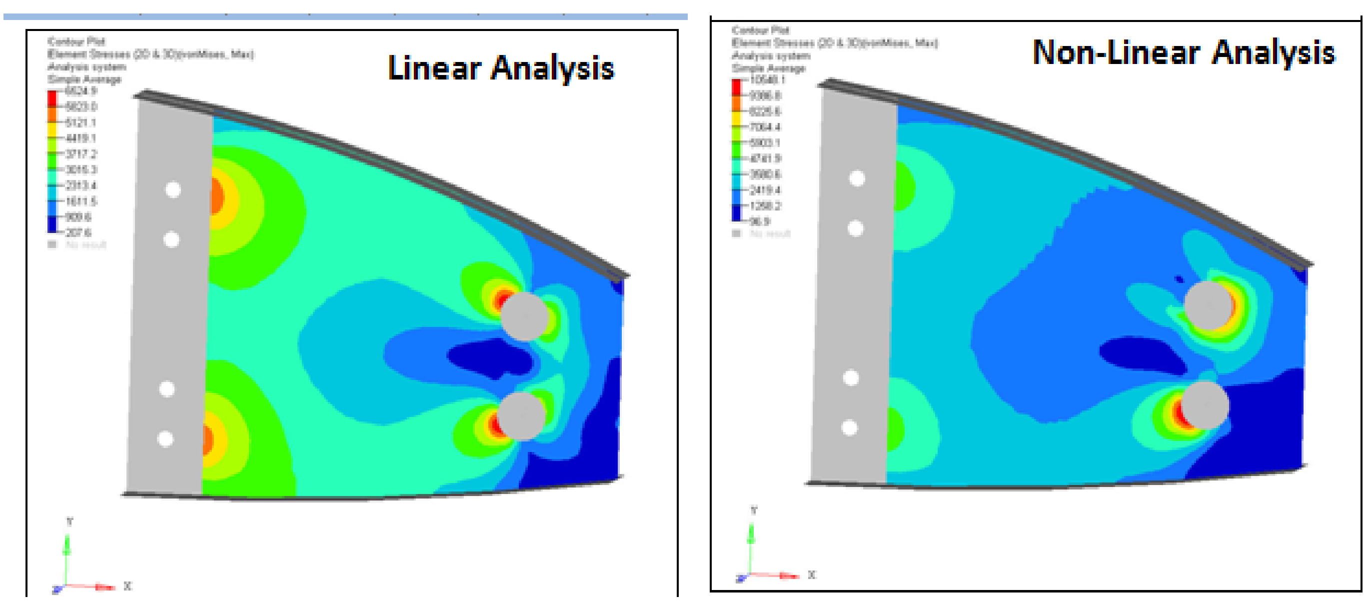

Figure 3: Not accounting for the boundary non-linearity and changing contact areas during an analysis can lead to errant predictions in the stress distributions throughout the part.

contact surfaces remain constant, and does not perform this calculation.

Figure 3 shows an example of a plate being held in position by two bolts. The image on top shows the results of a linear analysis, while the image on the bottom shows the results of a non-linear analysis. Comparing the images shows that the stress distributions and predicted magnitudes change between the two different solvers. The inability of the linear solver to allow the contact interfaces between the bolts and the plate to change as the load is applied results in significantly different stress distribution of the part and an under prediction of the stress level in the plate. Properly modeling this contact interface and identifying the high stress areas is important not only for evaluating the structural integrity of the part, but also to help avoid placing manufacturing defects such as weld lines in these high stress areas.

Structural finite element analysis is a very powerful tool that has opened the door for plastics in many different fields. The ability to validate a plastic part design and make critical decisions regarding the final design can save a significant amount of time and money. However, care needs to be taken to ensure the analysis is accurately modeling the physical system. Ensuring the non-linear effects of the plastic material, loading condition and boundary conditions are accounted for in a simulation will help designers and engineers make the correct decisions and allow them to bring their product to market faster.

If you would like more information regarding design validation or simulation, or other plastics issues, please contact The Madison Group at 608-231-1907, or email at erik@madisongroup.com.

For further information regarding product structural simulation read the following paper authored by the staff at The Madison Group (click on the link to access the document).

Effect of Fiber Orientation Anisotropies on the Structural Performance of Molded FRP Composite Parts

"Plastic Part Failure: Analysis, Design, and Prevention"

Engineers from The Madison Group in conjunction with the University of Wisconsin–Milwaukee School of Continuing Education will present a three-day course entitled, "Plastic Part Failure: Analysis, Design, and Prevention". The course will be held December 2-4, 2013 at the University of Wisconsin –Milwaukee.

This seminar covers a broad range of topics essential to understanding and preventing plastic failure. The most efficient and effective approach to plastic component failure is by performing a systematic failure analysis following a scientific method. Someone once said, "if you don't know how something broke, you can't fix it", and this certainly highlights the importance of a thorough understanding of how and why a product has failed. This seminar will introduce the attendees to information they need to understand how this is done. The material will include:

- Essential knowledge of why plastic components fail,
- The five factors affecting plastic part performance,
- The process of conducting a failure investigation,
- The importance of ductile-to-brittle transitions and their role in plastic component failure,
- Methods for understanding how and why a product has failed,
- Approaches to more quickly respond to and resolve plastic component failure,
- Methods and techniques to avoid future failures

The seminar will stress practical problem-solving techniques and will be utilize case studies to illustrate key aspect of plastic failure an prevention. Participants will gain a better understanding why plastic components fail, and how to avoid future failures by applying the knowledge learned.

For more information and registration contact Murali Vedula at 414-227-3121 or mvedula@uwm.edu.

The Madison Group Celebrates 20 Years of Plastic Consulting

Paul Gramann, Ph.D.

Twenty years ago, while I was in graduate school, the idea of starting a company occurred when my advisor, Tim Osswald, and I were in one of our brain storming sessions as we walked to his house from the University. At the time we were consulting for companies that needed help solving their molding problems and saw there was an opportunity waiting for us.

We knew if the company was going to be successful we needed people with good ideas, motivation, desire to help people, and an extensive knowledge of plastics. The one person we had to have to start the company was Bruce Davis – a fellow graduate student in Tim's research group. Never one to back down from a challenge and possessing the entrepreneur spirit, he was all in.

The name of the company is credited to our friend Dr. Erwin Baur of M-Base GmbH in Aachen, Germany. He had recently started his company and insisted that we come up with a name that will be easy to remember and accurately described our group. He mentioned that people knew us as the "guys from Madison"; thus the name The Madison Group was born.

After graduating from graduate school Bruce and I both had offers from prominent companies. We were looking at attractive, stable jobs or following this venture of unknowns and uncertainty. With the help and encouragement of Bruce's wife Lisa and my fiancée at the time, Stephanie, we turned down the offers and decided to step into the unknown world of running a business. We moved into a small office (approximately 12′ x 17′) in the University of Wisconsin- Madison research park and worked enormous hours trying to make it work. Besides wearing numerous "hats" as one has to do when starting a company, we did some out of the box things to stay a float. We started a stone company and sold/delivered solid natural stone benches during the evenings and weekends throughout southern Wisconsin. One month we made ends meet by bringing back ten cases of Italian chocolates from Germany and selling them at my father's convenience store.

The next biggest, and perhaps one of the most important, decisions we made was to ask/convince Antoine Rios to join the company after he received his Ph.D. in 1999. After later receiving his MBA, Antoine quickly infused a more business mentality into The Madison Group. He also convinced us that we needed someone that could run the "front office" and reduce our non-engineering tasks. Julie Porto was hired and rapidly made herself a critical member of our growing team.

We have hired many amazing people who have all contributed greatly to the success of the company. The Madison Group is made-up of an incredible team of people that are dedicated, smart, enjoyable to be with, and strive to help our clients. It is extremely important to us that our employees enjoy the work they do, the people they work with and the clients they work for. The success of The Madison Group is because of the wonderful team we have and the clients that we are honored to work for.

I look forward to the next 20 years with great enthusiasm as The Madison Group grows in knowledge, capability and people. Thank you to everyone that has been involved in making the first 20 years full of wonderful memories and contributing to the success of The Madison Group.