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HONORS PROJECT PROPOSAL

An FEA/Mechanical Behavior Study of Embedded Microvascular Channels Used In Self- Healing Smart Composite Materials

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ABSTRACT

Smart composite technology has become a growing field in industries today, whether aerospace, automotive or even commercial product development. Modern materials developed these days now see the utilization of embedded microvascular channels, a concept which allows for such materials to contain more biological motives, such as self-healing. However, structural studies of such technology have yet to show to be very clear, and thus it would be useful to observe the loading characteristics and behaviors associated with microchannels, particularly in locations where stress concentrations would be substantial. This study, which does just that, will observe and analyze such behaviors by using an ASTM standard open-hole compression coupon embedded with these microchannels. By doing a comparison with and without them, as well as varying the coupon structure and location of the channels with respect to the open thru-hole, the effects can be drawn out, and more detailed observations of the behavior of these microchannels can bring for conclusive direction in future microchannel design.

ACKNOWLEDGEMENTS

Special thanks to Professor Chris Hansen and Dr. Konstantine for providing their time and effort to making the most out of this study. Their encouraging feedback was very helpful and hopefully it helps to give some great insight into their studies with Aurora Flight Sciences, NASA and other applications. Also thanks to graduate student Andrew Burke of the UMass Lowell engineering department for further background knowledge in composites, as well as undergraduate student Mohd Irfan Anwar of the UMass Lowell engineering department for providing useful information and tips regarding the Abaqus-CAE software.

INTRODUCTION

In recent development, modern technology has allowed for the monitoring of structures to be more prompt and interactive and less costly. Materials have become more complex and light-weight (from simple conventional materials like metals to composites, etc.), and furthermore, the introduction to this has led to greater ability to use biological notion in these designs that can allow for smarter materials [1]. These smarter materials include the concept of self-healing technology, a design that is growing in industry and could be a beneficial part in reducing current inspection costs, fulfilling certain critical mechanical, chemical or thermal requirements, as well as source targeting during material wear of structures over time [1].

What Makes Structural Technology Living?

In the next years to come, material science and engineering will soon aim to understand the integrated property of materials that can allow it to become more nervous and more living and what this means in a realistic, business, and ethical standpoint. By integrating greater structural health monitoring (SHM) type technology with these smart materials, will there be a sense that structures can in fact use sensors within or adhered to itself to be able to fix itself as living organisms do, and can there be a solution to resolve the monitoring of structures, no matter the complexity? Currently, developments with electronic skin have been the closest to creating a “nervous system” that a material can be interacted with.

So how would these materials be able to fix themselves you may ask? Well one particular study with a growing outlook in which is currently starting to be implemented is the development of polymer materials that include a fluid that can bond together upon fracture or tare, particularly in the microscopic level of chemistry. Going further, this technology is now also in progress of being implemented in the more popular composite field, which involves the allowance for the inclusion of fluid flow in them, like that shown in Figure 1. This is a concept known as *embedded microchannels*, or *microvascular channels*, which would involve a circulated network of “tube-like” microvascular structures within the layers of material, similar to the circulatory system in complex living organisms. By adding this ability to allow self-healing agent (SHA) to fill in and harden cracks and damages in these composite materials, quite like the body’s healing process with a cut, the structure can fundamentally regenerate its strength

and prevent further propagation, a concept proven in today's research [2]. Figure 2 shows how these microchannels would be laid out with composite developed by Aurora Flight Sciences for their research project. However, because structures typically undergo frequent stress, it must be observed how these microchannels affect the structural integrity of the materials, particularly around holes and gaps.

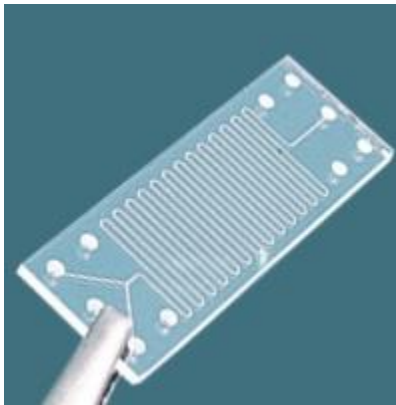


Figure 1: Microchannel-based Materials, like this Polymer Microfluidic Device (PMD), show a basic concept of how fluid can be run through a material



Figure 2: Microchannels being laid out on composite, which will be embedded under further layers [3]

Working forward, the development and improvement of Structural Health Monitoring (SHM) technology, which involves a simple way to monitor fatigue in structures without the need to use expensive current inspection methods, would be a good system to tie in with this technology in order to allow for healing that would require intervention to initiate the healing process. Figure 3 gives an example of the fusion architecture of a Structural Health Monitoring system and illustrates the process of how it works.

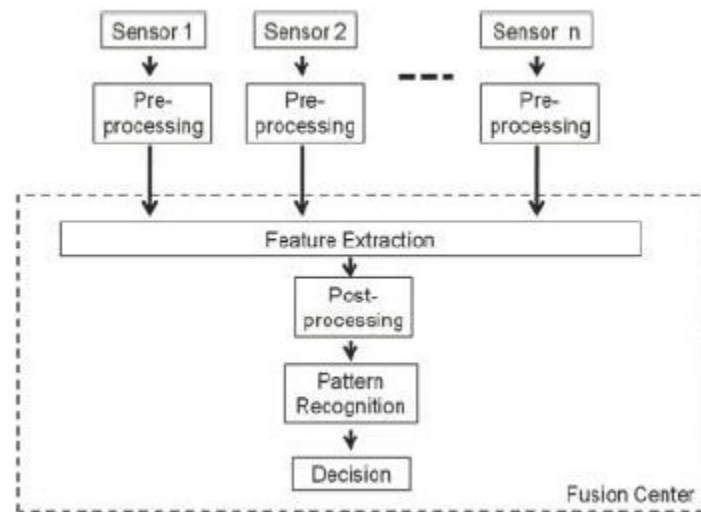


Figure 3: Fusion Architecture Example of SHM System [4]

Since this new technology is just starting to be used in industry, the progress in making smarter structures is very real, and with deeper study towards gaining deeper understanding, it can be achieved. Yet, there are still challenges to overcome, such as obtaining the ability to characterize and model such structures under various everyday environmental loads and conditions.

Why the Need for Finite Element Modeling?

When it comes to engineering in itself, structures will typically need to be run under not only mathematical verification, but also simulation and studies of how they will behave with their environment, especially if it's a newly developed structure placed in an environment that is difficult to conclude this behavior. According to recent study of embedded microchannel structures, the tradeoffs between mechanical performance and extended functionalities remain

relatively ill-quantified, and previous studies of the effects of embedded microchannels on structural capability have considered a small number of loading conditions and layups not typically used in aerospace structures [5]. Simply put, materials that involve embedded microvascular channels will typically occur in complex conditions, and experience or undergo different kinds of complex behaviors and stresses that can't just be clearly determined by eye, by mathematics, or even by simple testing environments due to the complexity of such a design. However, it can be assumed though that because stress concentrations are more prone to show and be magnified around areas where there are holes, crevices, cracks or damages, it would be a key approach to see how the microchannels behave under such a more realistic-type condition. Currently, NASA research has funded the need in studying these newly implemented self-healing composite materials with Aurora Flight Sciences, along with the ties with UML.

BRIEF DESCRIPTION OF DELIVERABLES

Methods Implemented - Embedded Microchannel Concept Design & Brainstorm

This study, which ties into current Aurora Flight Sciences and NASA research on self-healing composite materials, aims to address the characteristics and reliability of embedded microvascular channels near large crevices and how it affects the stresses of the material under displacing loads. Here, in addition to studying what happens to structural behavior with the addition of these channels, the key element to be examined is what exactly happens to the stresses of the material with varying location of the microchannels with respect to these holes and gaps (represented by Figure 4). This includes characterizing the stresses of not only a solid, isotropic structure, but also that of multiple layers of material, representing a composite-based structure.

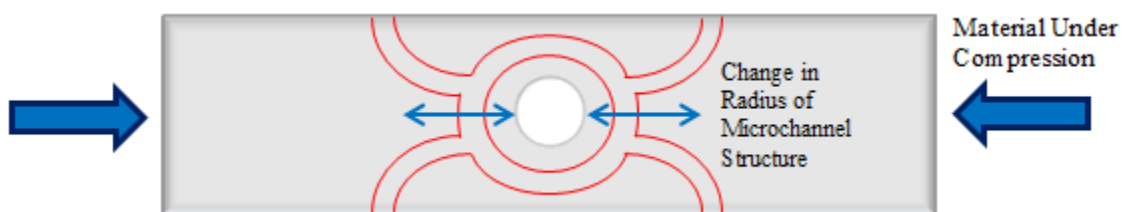


Figure 4: Test Design of Microchannels with Respect to the Hole

Therefore, for this investigation, both the properties of an isotropic material will be utilized (ie. steel), as well as those of a composite one. Abaqus/CAE software will be used to perform the FEA analysis using SolidWorks files of solid plates known as “coupons.” In order to perform the analysis, it must be first understood of the types of loading that can be inflicted on the material. Through research, it’s found that compressive forces will emit the greatest effects of stress, and is most desired. Therefore, this will be taken into account. The proper meshing will also have to be examined and understood for this.

After analyzing the results, and once a general relationship and behavior characteristic is analyzed, more complex structures could then be looked at. This includes having a chain of these microchannel systems, observing them in various geometries, or even observing them around tight bends, all of which can help to produce a relationship and behavior characteristic of the microchannels on the material being analyzed.

Materials Used & Background of ABAQUS Software

Abaqus/CAE, otherwise known as "Complete Abaqus Environment," is a software application used for both the modeling and analysis of mechanical components and assemblies (known as pre-processing) and visualizing the finite element analysis result. It has a wide material modeling capability, an ability to be customized, and it provides a good collection of multiphysics capabilities, including coupled acoustic-structural, piezoelectric, and structural-pore capabilities, all of which make it all the more interactive.

The specimen being used to test with is an ASTM standard open-hole compression coupon, defined by the dimensional properties shown in Figure 5. This allows for the ability to keep in a consistent window throughout this test and provide useful realistic testing input. The material specifics in this test will be carbon cast steel, and Twintex thermoplastic composite. The Young’s modulus of each material respectively are 30,000 ksi and 3,000 ksi, Poisson’s ratio for each is 0.3 and 0.272, and ultimate tensile strength is 60 ksi and 43.5 ksi respectively [6].

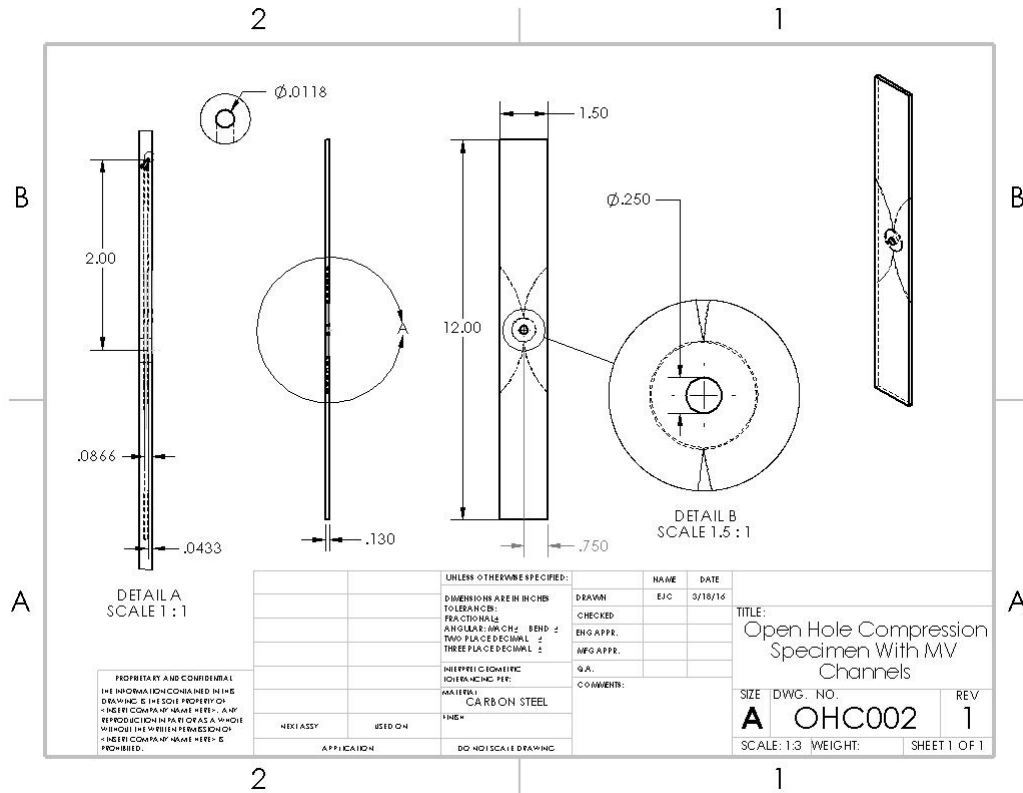


Figure 5: Open-Hole Compression Specimen with Embedded Microchannels

Dimensional values are further represented by Table 1.

Table 1: Dimensional Values of OHC Specimen

Specimen Dimensions (With and Without MV Channels)	
Length (in)	12.0
Width (in)	1.50
Thickness (in)	0.130
Open Thru-Hole Diameter (in)	0.250
Fillet Diameter of Thru Hole (in)	0.01
Microchannel Diameter (in)	0.0118
Diameter of the Channel Length Around Thru-Hole (in)	0.738
Depth of Microchannels (in)	1 st Layer: 0.0433 2 nd Layer: 0.0866
Fillet Diameter of Channels (in)	0.005
Number of Channel Entrances/Exits	4

Objective & Products to Be Presented

The goal is to understand the characteristics and results involved in producing Finite Element Models on microchannel OHC Specimens under specific forces and displacements. The specifics that are to be covered include:

- The significance of utilizing this technology
- The challenges associated with FE modeling microvascular channel embedded specimen
- The comparative analysis of modeling stresses and displacements between...
 - Specimen with and without microchannels
 - Varying microchannel diameters around the thru hole
- Utilizing a composite application in the FEA study
- Understanding effects of additional variables such as implementation of fillets along the channels
- Determining future outlooks associated with the results obtained

Presentation

For the final presentation, a detailed write-up will be completed interpreting and explaining the procedure made and results obtained. FEA models will be made and analyzed, and design illustrations will be used, shared through the use of power point and presented to the research team.

PROJECT SCHEDULE/TIMELINE

Table 2: Project Timeline – January thru April

Timeframe	Objective	Specific Goals
<i>Weeks 1-2 (Jan. 24 – Feb. 6)</i>	<i>Final Brainstorm of Topic & Narrowing of Specific Focus; Proposal Due</i>	Identify specific focus in the research related to capstone Turn in project proposal & honors project form
<i>Weeks 3-4 (Feb. 7 – 20)</i>	<i>Research Period</i>	Understand self-healing materials & history of microchannel application in materials Develop knowledge of current progress in smart materials Discover current related research on microchannels and problems that have already been solved
<i>Weeks 5-8 (Feb. 21 – March 19)</i>	<i>Initial FEA Analysis of Coupons with Microvascular Channels;</i>	Use Abaqus software to perform stress-analysis through loads on coupons with and without MV channels, varying microchannel location, etc.
<i>Weeks 9-12 (March 20 – April 16)</i>	<i>Review of Results & Improvement Period</i>	Understand meaning of results Go over w/ advisor on improvement strategies Determine how to improve on the analysis; perform additional testing
<i>Week 11-14 (April 3 – April 23)</i>	<i>1st Draft</i>	Organize & fully develop the first draft of report
<i>Weeks 15-16 (April 24 - May 6)</i>	<i>Final Draft</i>	Get feedback Complete the final draft
<i>Weeks 15 or 16 (Final Week)</i>	Presentation?	Present results
May 6, 2016	Thesis/Project Completion Form Due	Fill out & hand in thesis/project completion form

FEA METHODOLOGIES

The Finite Element models will be classified in two ways, by its maximum absolute stresses and by its displacements. The stresses include absolute principal, shear, and Tresca (or shear stress to cause yielding).

Meshing

Distances between nodes in the meshing elements were determined to be most accurate for the results between a size of 0.02 and 0.1 inches, without going passed the license limit of 250,000 nodes. To be more specific, meshing around holes was set to be a size of 0.02 inches between seeds, and meshing along the outer edges of the coupon was set at sizes of either 0.1 in or 0.05 in depending on the test. The important areas of focus here are the locations surrounding the hole and that of the microchannels themselves. In order to create the mesh around holes, partitions initially had to be made to divide the part up into four sections (two lines of partitioning per hole). This also would allow for simpler, cleaner meshing, providing more accurate consistency. The meshing type used in this study was primarily Tet, or Tri, meshing. This basically means that the elements are composed of triangles, rather than the standard quadrilaterals. This was chosen as a result of difficulty in meshing quad elements within the microchannels of the full and half-length isotropic tests. Hex, or Quad, meshing was however able to be used for the composite testing.

Application of Displacements, Forces and BC

In order to apply the forces or displacement boundary conditions, the face of one side had to be fully encastured, basically fixed in position with no freedom of movement in any direction. The parallel face directly opposite that of the encastured one (the other end) would then be set to have the uniform displacement or pressure force. For the half-length compression test, as seen in Figure 6, it was necessary to apply these displacements or forces on the faces where it is cut (since this is the location of which the stresses are to concentrate at). However, this would be the opposite for the bending test (Figure 7).

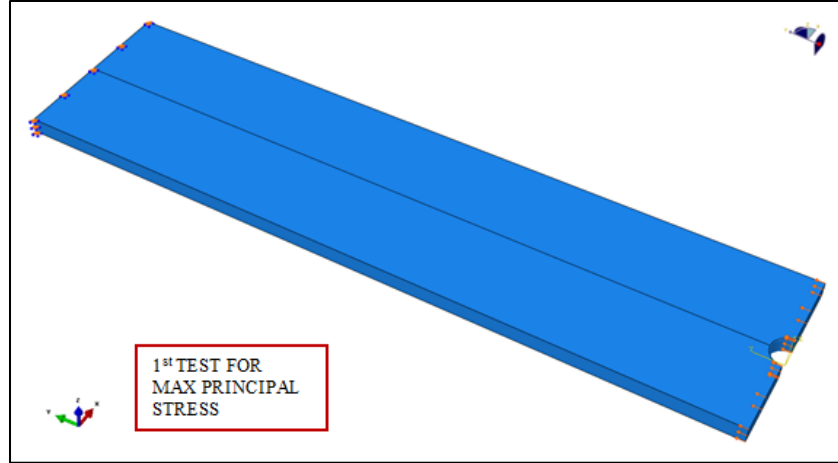


Figure 6: Applied Compression Force in Abaqus/CAE

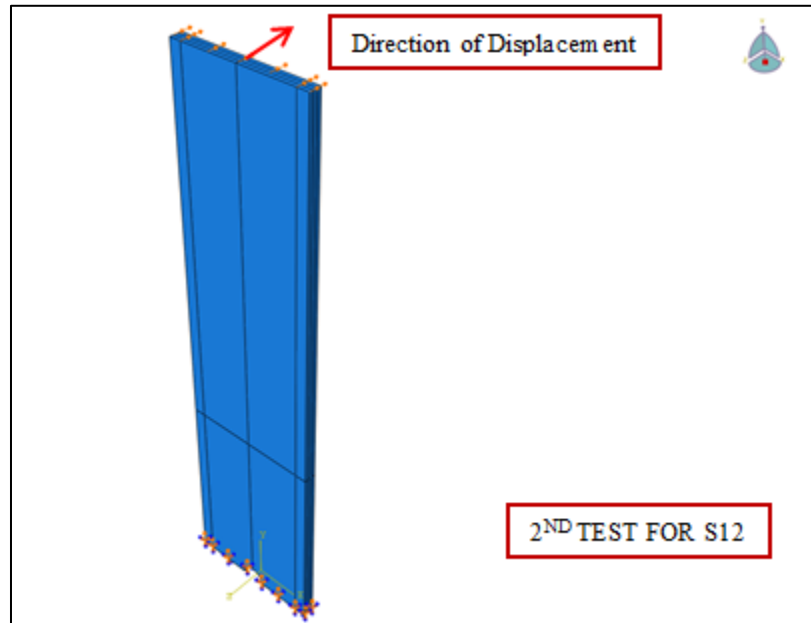


Figure 7: Applied Bending Force in Abaqus/CAE

Compression displacements were determined using Equation 1, where P is the load to be applied, L is the total length of the coupon, A is the cross-sectional area of the face where the force/displacement is to be applied, and E is the Young's modulus of the material.

$$\delta = \frac{PL}{AE} \quad (1)$$

Bending displacements were found by utilizing Equations 2 and 3. Here, W is the load at the tip, l is the total length, x is the distance of the load from the fixed point, E is the Young's

modulus of the material, and I is the area moment of inertia. For the inertia equation, b represents the longer length of the cross section, while h is the shorter.

$$y = \frac{Wx^2}{6EI} (3l - x) \quad (2)$$

$$I = \frac{bh^3}{12} \quad (3)$$

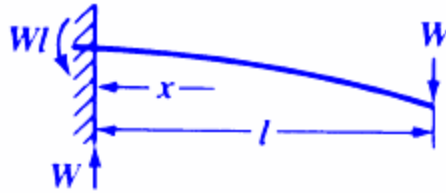


Figure 8: Representation of Bending Load with Variables

Table 4 shows the calculated values that were utilized for each test.

Table 3: Values of Applied Displacements and Forces

	Compression Displacement (in)	Bending Displacement (in)	Applied Forces (lbs)
Full-Length Test	1.0256×10^{-4}	-	50
Half-Length Test	2.0512×10^{-3}	-	2000
Composite Test	1.0256×10^{-3}	4.370	-
Diameter Variation Test	2.0512×10^{-3}	0.437	-

Addition of Fillets Throughout Microchannels

One of the more interesting variables that was considered throughout this test was whether the channels had fillets or not. Fillets are particularly designed to eliminate stresses at tight corners of intersecting faces. For this case, 0.005 inch diameter fillets were applied to the microchannels.

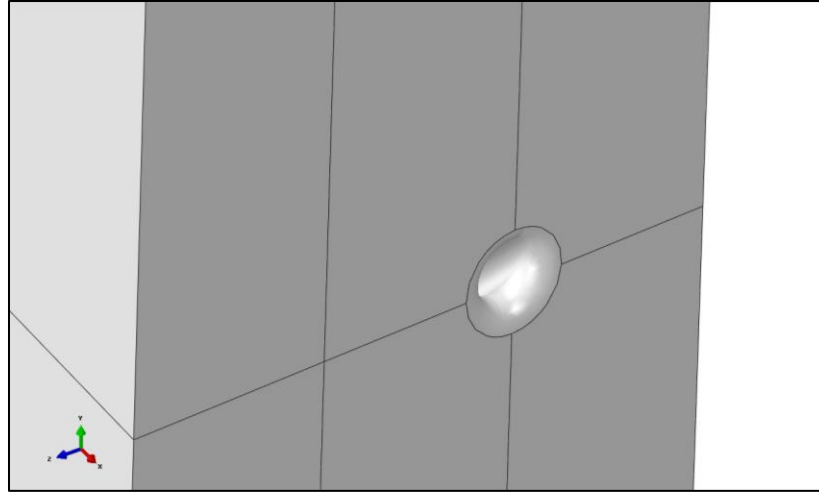


Figure 9: Addition of Fillets

Full-Length Compression Test

The first test, involving the full specimen placed under compression, will compare coupons both with and without microchannels. This was performed under two cases, one with a 50 lb force and the other with a displacement of the equivalent 50 lb force. For Case 1, this involved placing the face of one end under an encastured BC while setting the face of the opposite parallel end under a 1.0256×10^{-4} in displacement perpendicular into the specimen. For Case 2, the same would be done, only with a 256.4 psi pressure on the same face (equivalent to a 50 lb force placed on the entire area).

Half-Length Compression Test

For the half-length test, two different types of tests were to be performed under this condition. One was the re-application of compression on coupons both with and without the microchannels, and the other was changing the distance of the channels from the hole. The reason behind including such a test was for a couple of reasons: 1) the specimen is symmetrical along the midpoint of the coupon (thus half of this part can be neglected), and 2) a finer meshing could be implemented throughout the part, since half of the thousands of elements within the channels are removed from the equation. This is particularly important knowing the limitations of what is given to use this software, and also for the reason of cutting back on wait time.

The first test of microchannel vs no-microchannel comparison was again performed under two cases, this time with a 2000 lb force and the other with a displacement of the equivalent 2000 lb force. For Case 3, this involved placing the faces of the end with the hole under a 1.0256×10^{-4} in displacement

perpendicular into the specimen and the face of the opposite parallel end under an encastured BC. For Case 4, the same would be done, only with uniform 2000 lb forces on the same face.

The second test of varying the microchannel distance from the hole however was performed under two conditions, a compression displacement, and a bending one. The bending displacement will measure the shear stresses associated with it.

Composite Layering Test

Since this is a study of composite structures in particular, an analysis with layered materials was implemented. As shown by Figures 10 and 11, the Abaqus/CAE software has a particularly useful tool to create composite layering based on a 3D modeled, 2D plane representation of the coupon and channels. Each layer was created by selecting the faces of geometry associated with that layer. In total, 6 layers were used, all in symmetry. What this means is that the first three layers are essentially replicated and reflected along the mid-plane of the layers. The orientations of the fibers, from top to bottom, are 0° , 45° , 90° , 90° , 135° , and 0° .

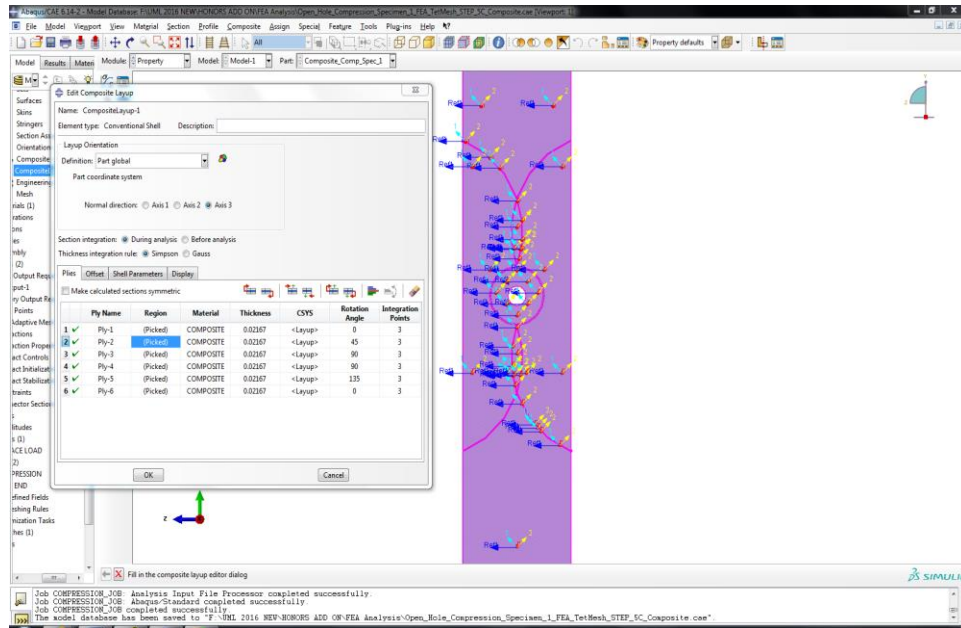


Figure 10: MV Composite Layering in Abaqus/CAE

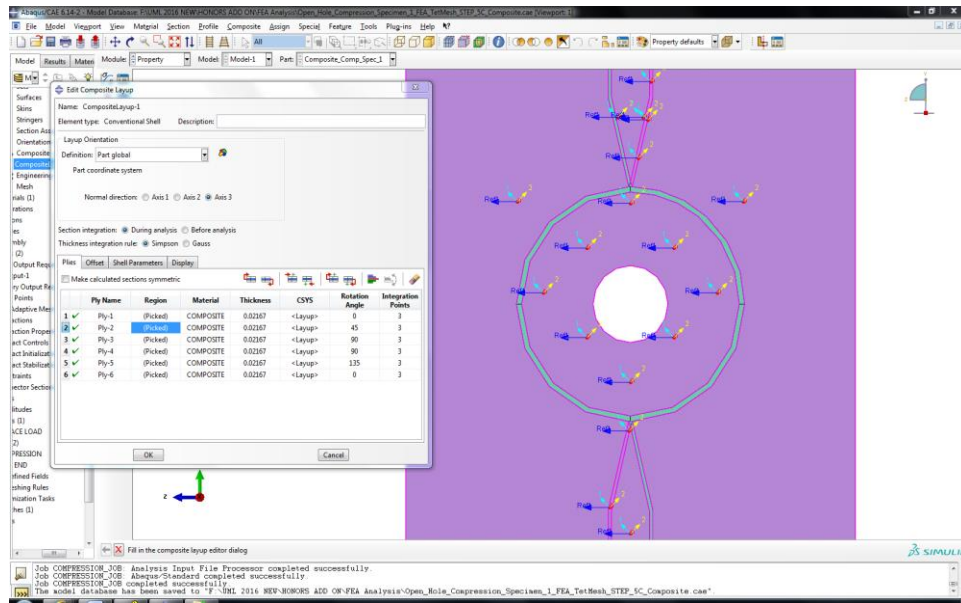


Figure 11: Zoomed View of MV Composite Layering in Abaqus/CAE

MV Channel Distance From Hole Testing

A key to this test is not only comparing a specimen that has or doesn't have embedded microchannels, but also how they are located within the material. In this case, it is important to see the changes associated with the channel distance from the hole on the coupon. By varying this “diameter,” as illustrated by Figure 12, four models were developed and compared in total, along with an additional model without any channels.

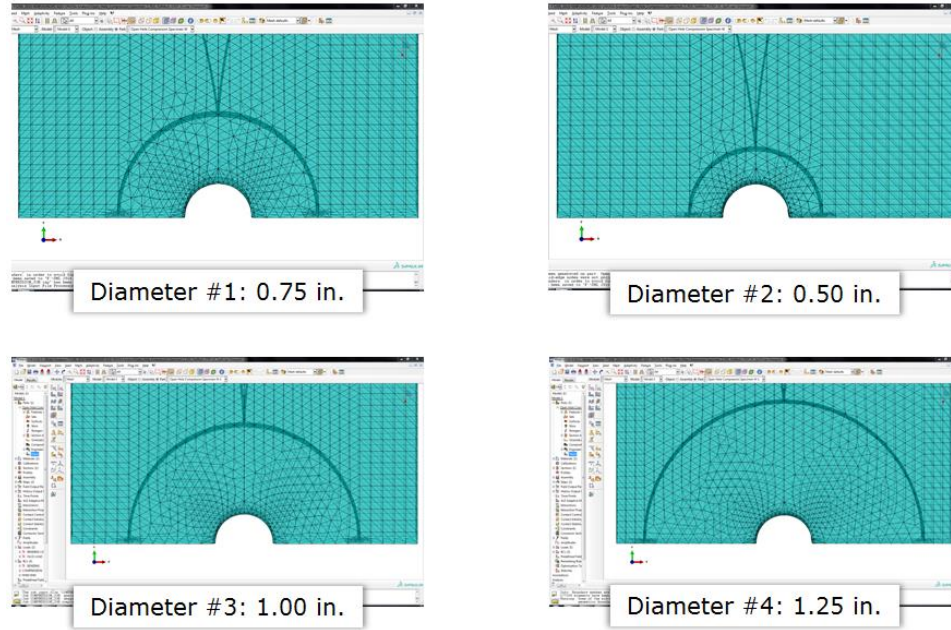


Figure 12: MV Channel Diameter Variation Relative to Hole

FEA ANALYSIS

Compression Testing Results – Steel

Based on full-length compression testing, it is found that the maximum principal stresses only slightly increase with addition of the microchannels, and even further with the addition of fillets. Under Case 2 however, there is slightly less stress observed by the specimen with channels of no fillets than that of the specimen without channels. Displacements also show to be at their greatest without channels, and least with channels and no fillets. Nominal stress was verified using $\sigma = P/A$, where P is the applied load and A is the area of the face of which the load is applied to. Seeing that it came out to be around 250 psi in the test, it is certainly close enough to the calculated value, which is 256.4 psi, meaning the results should be valid.

Table 4: Full Length Compression Test - With Displacement & With Uniform Force

Case	Variable	OHC Specimen w/ No Channels	OHC Specimen w/ MV Channels (No Channel Fillets)	OHC Specimen w/ MV Channels & Channel Fillets
1 (Solid Steel Test; Full Length Spec.) Displacement; Tet (Tri) Meshing	Applied Displacement (in)	1.0256×10^{-4}	1.0256×10^{-4}	1.0256×10^{-4}
	Nominal Stress (psi)	~250 (Expected = 256.4)	~250	~250
	Max Stress (psi)	818.0	819.3	821.5
2 (Solid Steel Test; Full Length Spec.) Uniform Force; Tet (Tri) Meshing	Applied Load (lbs)	50	50	50
	Nominal Stress (psi)	~250	~250	~250
	Max Stress (psi)	723.8	720.0	727.5
	Max Displacement (in)	9.439×10^{-5}	9.414×10^{-5}	9.429×10^{-5}

From the half-length test with much larger forces and displacements utilized however, this appears to show a different story. It is found that the maximum principal stresses this time slightly *decrease* with addition of the microchannels. For the load case, it slightly increases however, with a drop in the displacement.

Table 5: Half Length Compression Test – With Displacement & With Uniform Force

Case	Variable	OHC Specimen w/ No Channels	OHC Specimen w/ MV Channels (No Channel Fillets)	OHC Specimen w/ MV Channels & Channel Fillets
3 (Solid Steel Test; Half Length Spec.) Displacement; Tet (Tri) Meshing	Applied Displacement (in)	2.0512×10^{-3}	-	2.0512×10^{-3}
	Nominal Stress (psi)	~10.21 (Expected = 10.256)	-	~10.21
	Max Stress (psi)	33.020	-	32.990
4 (Solid Steel Test; Half Length Spec.) Uniform Force; Tet (Tri) Meshing	Applied Load (lbs)	2000	-	2000
	Nominal Stress (psi)	~8.465	-	~8.465
	Max Stress (psi)	20.95	-	23.77
	Max Displacement (in)	1.771×10^{-3}	-	1.757×10^{-3}

Compression & Bending Testing Results – Composite

With the composite analysis, stresses appear to again slightly increase under compression with the addition of microchannels. However, stresses will decrease under the bending load condition, especially with having no fillets in the microchannels

Table 6: Composite Compression Test – With Displacement

Case	Variable	OHC Specimen w/ No Channels	OHC Specimen w/ MV Channels (No Channel Fillets)	OHC Specimen w/ MV Channels & Channel Fillets
5 Composite Test (Full Length Spec.) Displacement; Hex (Quad) Dominated Meshing	Applied Displacement (in)	1.0256×10^{-3}	1.0256×10^{-3}	1.0256×10^{-3}
	Nom. Princ. Stress (psi)	~260 (Expected = 256.4)	~260	~220
	Max Princ. Stress (psi)	789.1	791.3	791.3

Table 7: Composite Bending Test – With Displacement

Case	Variable	OHC Specimen w/ No Channels	OHC Specimen w/ MV Channels (No Channel Fillets)	OHC Specimen w/ MV Channels & Channel Fillets
6 Composite Test (Full Length Spec.) Bending Load/Shear Test; Hex (Quad) Dom. Meshing	Applied Disp. (in)	4.370	4.370	4.370
	Nom. Princ. Stress (ksi)	0 – 178.7	0 – 147.9	0 – 161.8
	Max Princ. Stress (ksi)	178.7	147.9	161.8
	Nom. S12 Stress (psi)	0	0	0
	Max S12 Stress (ksi)	47.52	46.96	47.08

Diameter of Channel Variation Around Open Thru-Hole

Current design of the microchannel placement within the coupon has left it to be at a diameter of about 0.75 in. By adjusting this channel diameter around the hole through four different sizes and analyzing them under the same conditions and constraints, a correlation could be visualized, as represented by the chart in Figure 13. Since the 1 in diameter result appears to be a possible outlier (with a ridiculously high stress value), it was taken off the correlated chart. However, it may mean something as well. From this overall observation of results though, it is quite clear that by lowering this distance between channel and hole, the stresses slightly lower, but not by a whole lot. In fact, even when

comparing to that without microchannels, it only slightly ranges at 20 psi (if assuming the 1.25 in diameter result). For shear stresses under bending however, the numbers steadily incline more and more as the channels get closer to the hole. Combining both cases, it appears that having the channels at a happy medium appears to me the most optimal.

Table 8: Diameter Variation Around Hole Compression Test – With Displacement

Case	Variable	OHC Specimen w/ MV Channels & Channel Fillets				
7 (Solid Steel Test; Half Length Specimen) Displacement; Tet (Tri) Meshing	Channel Ring Diameter Around Thru-Hole (in)	0.75 (Control)	0.50	1.00	1.25	None
	Applied Displacement (in)	2.0512×10^{-3} (2000 lbs)	2.0512×10^{-3}	2.0512×10^{-3}	2.0512×10^{-3}	2.0512×10^{-3}
	Nom. Princ. Stress (ksi)	~10.21	~10.21	~10.21	~10.21	~10.21
	Max Princ. Stress (ksi)	32.840	32.990	54.140	33.000	33.020

Table 9: Diameter Variation Around Hole Bending Test – With Displacement

Case	Variable	OHC Specimen w/ MV Channels & Channel Fillets				
7 Bending Load/Shear Test; Tet (Tri) Mesh	Channel Ring Diameter Around Thru-Hole (in)	0.75 (Control)	0.50	1.00	1.25	None
	Applied Disp. (in)	0.437 (50 lb)	0.437	0.437	0.437	0.437
	Nom. S12 Stress (psi)	0	0	0	0	0
	Max S12 Stress (ksi)	47.150	54.250	47.900	48.270	46.740

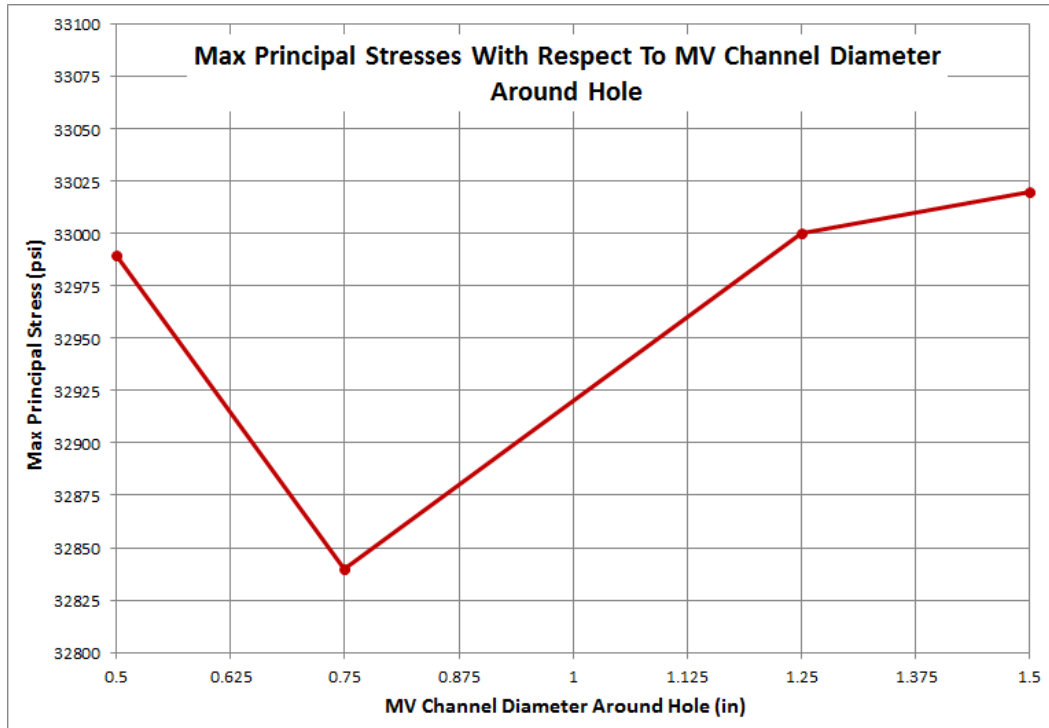


Figure 13: Correlation Between Max Principal Stress and MV Channel Diameter Around Hole

MV Channel Stresses

Much of the largest of stress concentrations has appeared frequently to concentrate at the open-hole in the middle of the specimen, rather than the channels themselves. This is important to note in this experiment, as the key to good design is minimizing the stresses that would occur within the channels themselves, thus avoiding imminent failures in those areas. However, some areas of stress concentration do reach high enough levels at the areas where the channel joints occur within the specimen. This appears to be more of a concern as the input force increases. However by the time the ultimate tensile strength of 60 ksi is reached, it is more likely that failure will first occur at the center open-hole. A good representation of this was done by selecting the elements within these joint areas (as shown by Figure 13) and performing stress plotting of these selected elements (Figure 14). The max stress obtained from this particular test was 32.99 ksi, but it can be noticed that the stress in the microchannels appears to reach up to about 26.5 ksi, which is significant. New approaches will have to be looked at to minimize this.

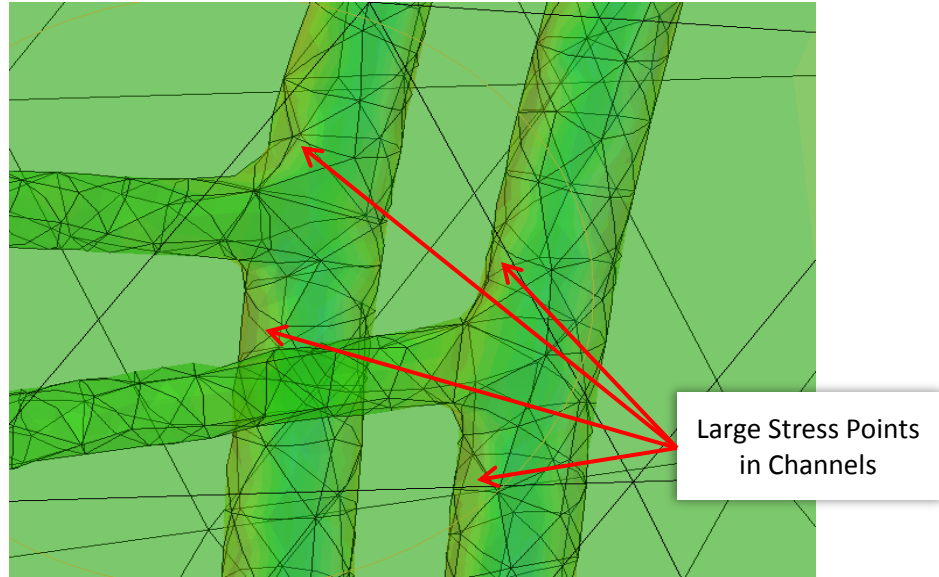


Figure 14: Zoomed Representation of Elements Involved in Microchannel Joints

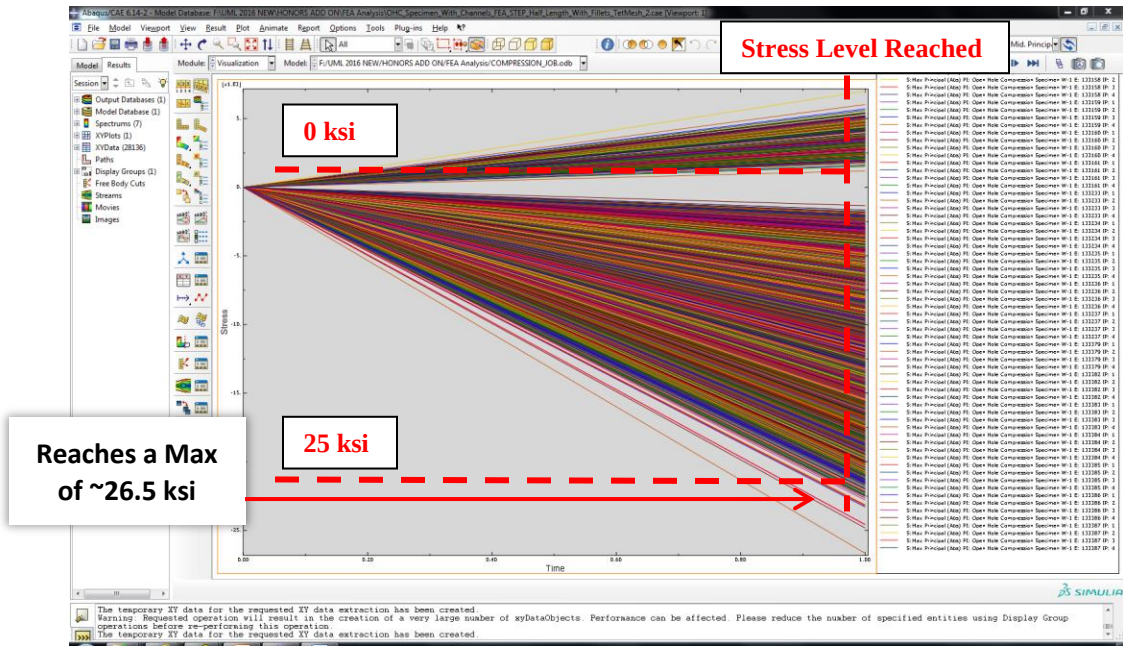


Figure 15: Stress Performances of These Elements

In addition to that, obtaining a good accuracy of the stresses that are occurring within the channels has proven to be a difficult task. For instance, as shown by Figure 15, the some elements show to be too large of a size and involve many sharp corners between each other, thus providing only an estimation of the true stress values.

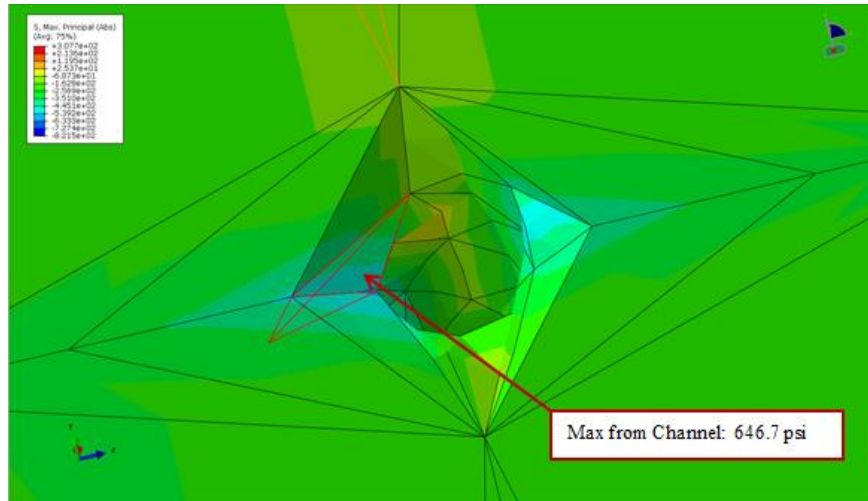


Figure 16: Mesh Quality of Some Specific Channel Elements

Fillet Analysis

The addition of the fillets appears to have very minimal effect on the channel stresses themselves, however it does show to result in greater stress accumulation within that area. This is likely a result of the stresses being more concentrated in that area, especially since the elements of that plane of axis on the face of the specimen perpendicular to the plane of which the displacement is applied are being compressed and shifted lots more than what the specific uniform layout of elements within the microchannels are experiencing (which in a sense allows for stresses to be distributed throughout them). This concentration can be seen with both the full-length test and composite test, shown by Figures 16 and 17. With the first figure, it can be seen that the max stress element from the channel is 523.5 psi, but with the addition of fillets, this stress value increased a bit to roughly 646.7 psi. The max principal stress relative to these tests is 819.3 psi and 821.5 psi respectively for no fillets and with fillets.

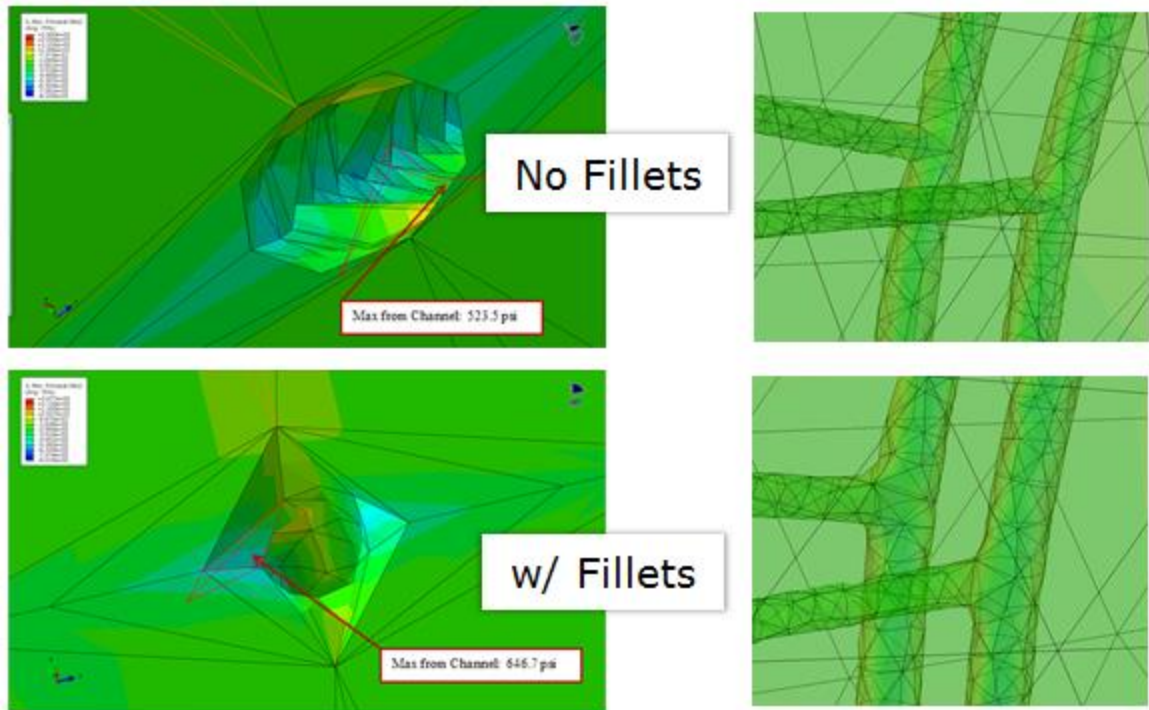


Figure 17: Full Length Test – Fillet/No-Fillet Comparison Under Max Principal Stress Component

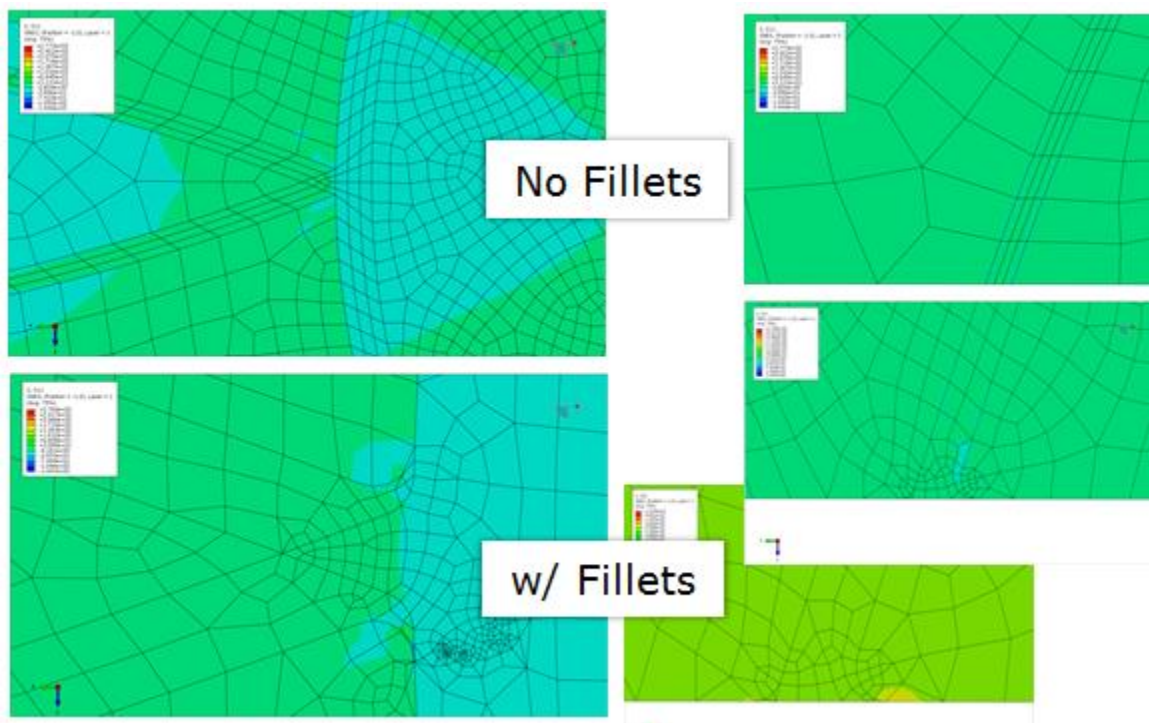


Figure 18: Composite Test – Fillet/No-Fillet Comparison Under S11 and S22 Stress Components

In the half-length compression test, the fillets of the microchannels show to reach a value of 26.907 ksi for the side exits (Figure 18), while the ones on the bottom near the thru-hole show to reach a value of 14.083 ksi (Figure 19). This is fairly close to the maximum stress value of 32.99 ksi, which occurs at the open thru-hole.

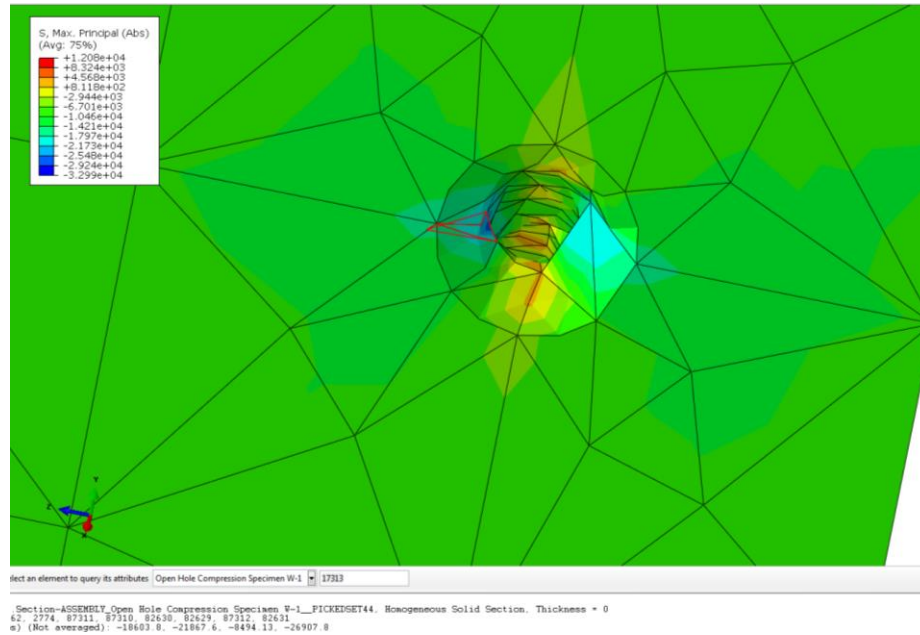


Figure 19: Half Length Test – Fillet of Side Microchannel Exit Under Max Principal Stress Component

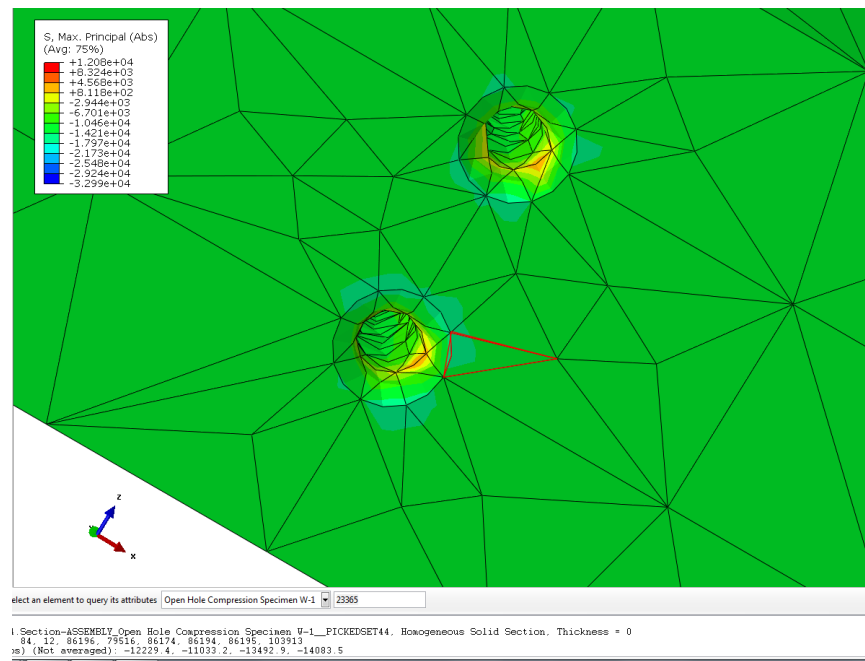


Figure 20: Half Length Test – Fillet of Microchannel Exit Near Thru-Hole Under MP Stress Component

Between this, the full-length test and the composite tests all mean that there are some heavy concentrations of stresses in these areas. However, because the values that reach even closer to the max are concentrated at the open thru-hole, this will still mean that failure will occur at that particular location before it ever reaches the microchannels and their corners or fillets.

CONCLUSION

This study has shown the minimal variations associated with utilizing the embedment of microvascular channels in open-hole coupons. Based on careful consideration of elemental, dimensional and variable consistency and accuracy of material properties, there is a confidence that the results give useful evidence to claim the following...

1. The stresses and displacements will vary, whether comparing with and without microchannels or changing diameter size of the channels around thru hole, but in **very miniscule amounts**
 - Stresses appear to be **slightly higher with channels** than without under compression, vice-versa under bending
 - However, with higher applied loads/displacements, this appears to *reverse* itself under compression, and the values are instead found to be **lower**
2. Including the microchannels however leads to **large observable stresses** forming within them, particularly where they branch off and/or exit the specimen
 - Range from about **64 – 82% of the value of the maximum principal stress**
 - These values **do not exceed** those at the thru-hole in the middle, and thus will likely not experience failure before the hole does
3. As far as microchannel positioning, it was found that placing the channels closer yet at a happy medium, particularly at **~0.75 in** from the hole, would be the most optimal; this even produced slightly lower stresses than the trial without embedded microchannels
 - This will likely vary depending on dimensional ratios
4. The meshing type appears to have no major effect, nor does the use of fillets
 - However interestingly, including the fillets appears to slightly raise principal stress values

FUTURE OUTLOOK

For future study on embedded microchannel FEA, this test should be re-performed using finer elemental sizes , as well as include other variations of variables to consider in this test, such as the number of layers, orientation, thickness, and density (amount) of microchannels. A correlation should be studied in greater detail between the max stresses produced and channel location, as this test has only covered a starting observation. Other methods of studying and performing the composite test may also be helpful, as there are bound to be errors associated with the current one (seeing that creating plies in the manner used from this test does not form round microchannel cross-sections). Larger loads should also be carried out further in these tests, and more complex structures would need to be utilized to understand true, realistic behavior of including embedded channels.

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