Ceramic Chip Capacitors "Flex Cracks"

Understanding & Solutions

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F-2111 1/98

"FLEX CRACKS"

INTRODUCTION

If you are familiar with the series of KEMET Engineering Bulletins, you may recognize the slant on the presentation. The KEMET Bulletins are presented in the spirit of improving the reliability, quality, and/or performance of the end product in the hands of the eventual customer, the consumer. The readers of these Bulletins have generally been very appreciative of this approach. KEMET presents the information as best we know it, and then challenges the process engineer or designer to accept a part of the responsibility to improve the overall performance. This Bulletin is also presented in this tone.

Why is this important enough to take the lead paragraph in the Bulletin? In this case, (eliminating or minimizing failures of ceramic chip capacitors caused by flexure of the circuit board after soldering) the majority of the responsibility will belong to those who design and assemble the circuit board and its product package.

KEMET (and others) have performed numerous experiments, tests, and analyses. This data and some analyses of the physics behind it will be presented in the opening sections. These analyses indicate that the ceramic capacitor in chip form has limitations that are basic to its physical properties. These are not a result of poor quality, poor process control, or poor material selection. The data and analysis also show only minute differences in performance between manufacturers and that these cannot be counted on to improve the performance of the end product.

As a result, the major responsibility lies with the user of the ceramic chip. This does not mean that all users will have problems, or that the parts are so weak as to generate major concerns. The parts have been used very successfully for many years without major problems, and can continue to be used with great success. The care that needs to be taken is quite reasonable, and with some understanding the user can be comfortable that the parts will perform as needed. When failures occur because of excess flexing, there needs to be some understanding of the reasons and where to look for the cause and improvements. This Bulletin will present numerous suggestions for the most likely places to look for sources of stress that could introduce these failures, including many that are not normally obvious. Design and process suggestions will also be included. In addition, we will give analysis tips to help determine if your sudden rash of failures is a result of poor quality on the side of your supplier, or the result of flexure stresses applied during or after the assembly process.

Are you still with us? Great! If you are having doubts, at least read the next few sections. We think you will continue.

THEORETICAL AND TEST INFORMATION

Ceramic chip capacitors are usually the highest-used surface mount part on any given board. They must be very reliable and robust to ensure that the end product performs within the customer's expectations. Over the last 10 years there have been many improvements in the thermal and mechanical robustness of these ceramic chip capacitors. One of the perplexing failure modes that remains, however, is a particular type of crack that we refer to as a "flex crack." The flex crack may occur when a circuit board is flexed or bent abnormally after the chips are soldered in place. KEMET and many others have investigated the "flex" failure mode. All of the work has confirmed that the failure results because the parts are stressed beyond the material strength, and not because of some underlying lack of quality or process control measure. The measure of the mechanical strength applicable to flex stresses is the Young's Modulus of Elasticity. When a force is applied to a material, the measure of the force per unit area is referred to as "stress." The change in length per unit of original length is referred to as "strain." The elastic region is the region where stress can be applied to a material, and when the stress is relieved, the material returns to its original dimension. When the stress exceeds the elastic limit, the material will not return to its original dimensions. Young's Modulus of Elasticity is the ratio of the stress to the strain in the elastic region. It is a constant for a given material.

Young's Modulus has been measured for C0G, X7R and Z5U materials. The table below shows typical values of Young's Modulus for these dielectric materials in different units.

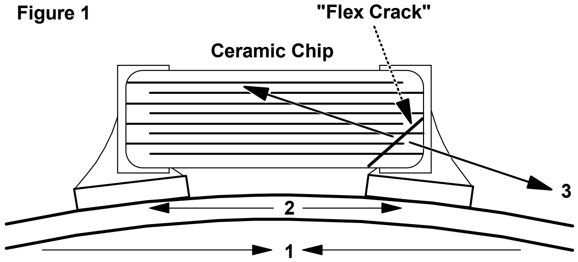
Dielectric Material	Young's Modulus (Kgf/Cm^2)	Young's Modulus (MegaPascalsMpa)
C0G	$1.2 \sim 1.3 * 10^6$	$1.3 * 10^5$
X7R	$1.1 \sim 1.2 * 10^6$	$1.1 * 10^5$
Z5U & Y5V	$0.9 \sim 1.0 * 10^6$	$0.9 * 10^5$

When stress (Kgf) is applied to the cross-sectional area, in the area the solder is making contact with the chip, a certain strain occurs. The ratio of the stress to the strain in the elastic area is Young's Modulus. Failure of ceramic capacitors appears to occur when the strain is in the 1300 to 2500 μ strain range. (1 Kg of Force is equal to 1 Newton.)

Figure 1 shows the type of stress applied to the ceramic when the circuit board is flexed.

The "flex crack" is distinguished by a unique signature. When a ceramic capacitor is known to have failed because excess bending stress was applied to the board, the resulting crack in the part always starts at the inside of the termination where it joins the circuit board pad. The crack then continues up through the capacitor. For low-fire technology ceramics, the crack will travel at a nearly 45-degree angle such as that seen in Figure 1. For high-fire technology ceramics, the crack will travel on a more vertical path. Depending on the severity of the stress, the crack may or may not travel to the top of the part. The shape of the flex crack also seems to change as chip thickness varies. The key is that the crack initiates at the intersection of the termination and the inside of the circuit pad. Failures will occur whenever the crack travels through two opposing electrodes.

Figure 1



1. Bottom side of board in compressive state
2. Top side of board in expansive state
3. Ceramic in Tension as a result of the applied stress.

KEMET and others have performed significant test programs to characterize this unique flex crack. The results have been reported in KEMET Engineering Bulletin titled "Capacitance Monitoring while Flex Testing" (reference 1), a Murata publication titled "Bending Strength Technical Data" (reference 2), and others (such as references 3 and 4). Excellent test and theoretical correlation is reported. Excerpts from these publications are not going to be republished here. They are available from the authors' companies for those interested in all of the details. These publications do include very good information on test methods and test fixtures. What is also of interest is the impact of some variables on bending strength. The published reports as well as other unpublished works have confirmed that:

a. Solder fillet size impacts bending strength. Larger fillets cause decreases in strength. In the same way, the circuit board land pattern area impacts bending strength. Narrower pads increase the bending strength. That is one reason behind KEMET's suggested wave solder pads being narrower than reflow solder pads.
b. Chip length impacts bending strength. The longer chips (i.e., 1206) do not have as much strength as shorter chips (i.e., 0805).
c. Dielectric materials impact bending strength. The C0G materials are superior to the X7R materials, which are superior in turn to the Z5U and Y5V materials.

d. The circuit board (PCB) thickness impacts bending strength. The thicker boards are more rigid andapply more stress to the chip. (A 1.6 mm PCB thick board will result in more failures than a 0.6 mm PCB when the same stress is applied.) There may be some relationship for the PCB material as well. The defining measure is Young's Modulus for the PCB.
e. Some published data indicates that chip thickness increases bending strength. This may be confounded by measurement parameters. Other data does not seem to support an increase in bending strength with chip thickness, and we believe this to be more accurate. See item f below.
f. Some capacitor designs have more cover layers before the active layers are reached. These parts may indicate a superior bending strength than ones with active layers closer to the outside of the capacitor. This indication is a result of the parameter (capacitance change) used to determine the breaking point. In fact, the ceramic has most likely cracked before the capacitance indicates the damage. It is best not to count on this as the crack may propagate with time or additional stress.
g. Capacitor termination width also has an impact on bending strength. Chips with wider termination bands have greater flexural strength. The wider band has the same effect as reducing the chip length (see item b and reference 4.)

Having determined these differences, it is still important to recognize that the improvements are minor, and not enough improvement can be obtained to allow the user to be inconsiderate of the need for care.

ADDITIONAL TEST DATA

In addition to the data above, KEMET and others have performed numerous tests investigating the flexural behavior of ceramic chips.

One of the most interesting was a "round robin" series of tests promoted by a major OEM customer. Since the program was sponsored by a customer, the detailed data is not available for distribution. We can, however, feel comfortable in sharing the test program and a summary of the results.

The customer requested numerous batches of a single part number from each of 7 different ceramic capacitor suppliers. These different capacitor suppliers represented a good cross-section of different technologies. The customer took the parts and sorted them into seven groups of blind samples. Each of the suppliers was then given these blind samples and asked to perform flex testing to an agreed upon standard. (Each supplier was given samples from each of other suppliers and his own for testing.) Each supplier was asked to mount the parts using two methods: reflow solder and wave solder. The number of cells then was 3 (batches) x 2 (solder methods) x 7 suppliers —— or 42. Each supplier returned the test results to the customer for analysis and regrouping. KEMET assisted in the analysis of the data after it was regrouped.

The results? All of the data indicated little difference in flexural strength within all of the cells. The differences noted were minor and easily within the variations expected because of differences in solder height, board materials, and test methods. There was one interesting complication. One of the suppliers chose to use a different test method, and obtained results different enough from the rest that the customer sponsor was interested in exploring it farther. KEMET agreed to host the customer and the other suppliers to conduct comparison tests on both KEMET and the other suppliers' parts. The results were predictable, and the differences in test methods revealed the difference in the previous results.

In addition to all of the investigative testing, a test program was conducted which attempted to find a link between flex test results and quality or process control differences. Parts of 1206 X7R 0.1 uF as well as 0805 X7R 0.1 uF were selected from a number of production lots. One hundred pieces were selected from a large number of batches. More than 2500 pieces of each were tested to destruction in the flexural mode. The parts were analyzed in an attempt to locate any defect site, or any indication of reason for failure. Besides defects, other items such as termination porosity, grain size, bandwidth, and porosity of the dielectric material were all considered. No anomaly, or indication of any differences, was found in this test program. This verified our earlier theory that the failure mode is related only to the mechanical strength of the dielectric.

Many test results have been compared to observe batch-to-batch and within-batch test results. “Within-batch” tests have shown excellent repeatability. Samples that were tested on the same day, on different days, and by different test operators, have all exhibited remarkable similarity in results. The curves almost fall directly on top of each other. Batch-to-batch testing has shown minor differences in results. The differences are less than 1 mm, and are with in the margin of repeatability.

On occasion, boards are returned for part analysis, with visual indications of test probes being inserted into the solder fillet (either directly in the fillet or in solder on the termination). One possibility was that probe forces may result in a crack similar to the flex crack signature. Test programs proved this false. The test probe did not duplicate the flex crack signature.

You know, this is great. You are still with us. Now we are going to move on to areas that we hope will assist you in determining if you have a problem, finding the most likely cause of the problem, and what can be done to minimize it. We hope you are still interested. We know you will benefit from the following.

Analysis (Are There Flexural Problems?)

Suddenly, ceramic chip capacitors are failing on your boards, maybe in significant quantities. Analysis of the circuit layout shows they are located in the same 1, 2, or 3 spots on the board. This pattern itself is a pretty good clue that the failure mode is going to be “flex cracks.” You can find this out for yourself in a very simple part analysis. KEMET, and other manufacturers, almost always want to get the failed boards back so that they can do a complete analysis and not be concerned about secondary damage. Sometimes there are other clues on the boards that help determine the root cause of failures. In this case, there are numerous failures, and if you are careful, you can get to the root cause without damaging all of the evidence. If your analysis does not indicate flex, then there are still plenty of failures for the capacitor manufacturer to analyze. If there are one or two failures, make sure you send the board back to the capacitor manufacturer to get the best analysis possible.

The reason the “flex crack” failure mode is probable lies in the improvements capacitor manufacturers have made in the performance of their product. If you are using a mainstream manufacturer’s capacitors, it is very unlikely that you will experience large amounts of quality-related failures in the same repeated locations on the board. Of course, it can happen. Be cautious in your analysis. If you are not using a mainstream capacitor supplier, you will want to work very carefully with this supplier during your analysis.

Step 1. Look at the location data and select the one with the most failures.

Step 2. Very carefully remove a few parts. We recommend hot air desoldering tools, removing as much of the solder as possible, and weakening the glue (if used). Both solder joints should be liquid during the removal of the chip. We suggest that you apply lateral force to remove the chip as opposed to lifting it from the board. (Before removing, you may want to mark the top of the chip with an ink marker.)

Step 3. After removal, very carefully and slowly sand the bottom of the chip until the solder and termination have been removed. Use fine grit sand paper. Do you see a crack similar to that shown in Figure 2? It will follow the line where the termination was. If so, you have flex cracks. This crack may not track all the way across. If the flexural stresses were applied more in a twisting manner, the crack may only go part of the way across.

Step 4. To do additional analysis, you may want to put the chip in “quick-mount” or some other mounting epoxy. Be careful here. If your lab is not used to mounting the parts, and selects the wrong material or cure cycle for the epoxy, cracks of various types can be induced during the mounting process. It would be a good idea to practice on some fresh parts right out of the tape. After mounting, grind a little from the side. Do you see the cracks shown in Figure 3? If so, you have flex cracks.

Step 5. If you didn’t see flex cracks, involve the capacitor manufacturer in any additional analysis.

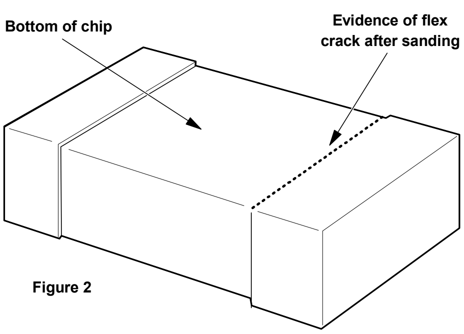


Figure 2

Detective Work and Solutions

Are you still with us? Did you find flex cracks in your own analysis, or has your capacitor supplier reported that your process introduces flex cracks? The next challenge is to isolate the cause of the board bending that is leading to the stress that causes the crack. Then preventive measures can be implemented.

The first step is to isolate the locations of the failures. Most often, in the case of flex failures, the failures are located in 1, 2, or 3 spots. Based on the location of the parts, a likely process or handling stress can be found. Processes after solder attach are the ones of interest. Second side solder processes might also be involved.

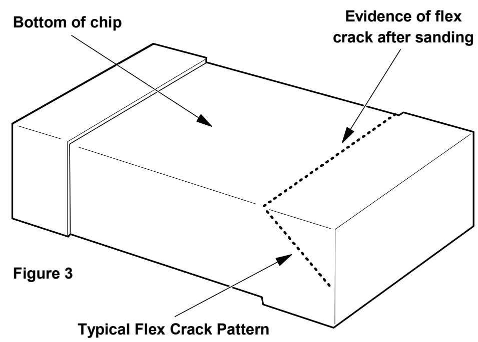


Figure 3

The second step is to look at possible causes for bending stress at the part locations involved.

A. Chips near the edge of the board are most susceptible to damage by flex. In this category, parts placed perpendicular to the edge of the board are more susceptible, and parts placed near depaneling tabs are most susceptible. This would include multiple board panels as well as trim tabs used to make the panel square for assembly processing.

Parts near depaneling tabs: If the location of the failing part is near the interconnecting tabs, the most likely cause of flex failure is the method of separating the individual circuit boards. History has shown this location to be a high stress point. To prevent flex failures, three important measures are suggested.

1. In circuit layout, keep all ceramic capacitors as far from the depaneling tabs as possible. For those nearest, make sure the parts are placed perpendicular to the direction of bending.
2. Board Considerations: Have your circuit board panel manufacturer drill small holes on the break line of the interconnecting tabs to make them easier to break. Most circuit board manufacturers

are familiar with this technique and may have examples for you to choose from. IPC 782 A (Surface Mount Design and Land Pattern Standard) has some examples of these as well. To order IPC 782A, contact the Institute for Interconnecting and Packaging Electronic Circuits. You can find them on the Web also at http://www.ipc.org.

3. Panel Separation Methods: In choosing a depaneling method, make sure that the boards to be separated are firmly held in a fixture that prevents them from being flexed. Common types of depaneling processes include many likely to cause flexure failures if the parts are close to the edges.

   The least expensive (most dangerous and most inconsistent) process is the handheld, manual-break process. The operator may hold the board at any location, and in most cases attempts to apply as much stress as possible.

   Another dangerous choice is the process whereby the operator breaks the board by using a straight edge (edge of a workbench, or even some provided tooling) to bend the boards over. The concerns are the same as those of the handheld process.

   A third process is depaneling with a shear. Sometimes this process includes fixturing to hold or locate the board for the shear. However, the forces applied are almost always so strong that the board actually jumps off the tooling fixture.

   Yet another, but more uncommon, process is the use of a pizza cutter type blade with some fixturing to hold the boards. This can be effective if the board thickness is slim, and the fixturing is designed to keep the board from moving. Since this method is usually employed in low-cost, high-variety applications, good tooling is not common, but most important.

   One of the best (and most recommended) processes involves routing the circuit tabs. This should be coupled with very good fixturing to hold the boards in place. Yes, we know this is more costly. The prevention of failures of product with your company's name and reputation has to be worth more than this small incremental cost.

   Similar failures can be caused where parts are located along the edges of paneled boards that are scored to be broken on the edges. This type of paneled board is less common today than it used to be. However, it is still worthy of mention. The break method most used with scored boards is usually one of the poorer ones, either by hand, or by breaking along a straight edge. Good fixtures are generally not employed. As mentioned above, these are high-stress processes.

B. Parts positioned near holes in the circuit board used for board positioning during product assembly, testing or other processing, also have been found to fail in a flexure mode. To prevent these failures, two important measures are suggested:

   1. Again, in circuit layout, keep parts away from these holes.
   2. Most important, check that the centers of the holes are where they are supposed to be, and that the pins, bolts, etc., on all the mating fixturing and assemblies are on these same centers. Also check that all of the pins, bolts, etc., are the correct size, with enough clearance to ensure the that board can be placed easily on the pins.

      Sometimes the detective work for failures around these features can be made easier. Inspection of the inside of the circuit board holes may show wear or rubbing on one side. This could indicate that the board had to be forced over the pins, and most likely was flexed to put it on the pins.

C. Parts positioned near holes where mounting screws are assembled with automatic tools such as nut drivers or screw drivers also are in high stress areas. The parts should be as far away from these areas as possible. The stress can come from movement of the board during the process or from stress applied by the automatic tool.

D. The chip placement process can also be a high stress process. We did say that processes of concern are those after solder attach. The second side placement process does come into play when the first side chips have already been soldered. Items of concern during the placement process usually involve the location of the board support pins (under the board) and excess over-travel of the placement nozzle. The usual bottom point of travel of the nozzle should not exceed the top of the board. Placement forces usually should be in the 100- to 300-gram force area in a static condition. Pins on the bottom of the board should be sufficient to prevent the board from flexing, and should also be kept away from any component. The vacuum nozzle should also be maintained to keep contamination from increasing the nozzle friction.

E. When leaded parts are placed after the surface mount chips are soldered, the leaded parts placement process should have the same care as the SMD process mentioned above. Automated processes might not incorporate good support for the board, causing bending of the board. Also, pay attention to the proximity of the lead clenching tools on the placement machine to the SMD parts. Manual insertion lines should also have good fixturing to support the board during assembly. This is especially important when large parts such as connectors or magnetic components are inserted in the board.

F. Automatic test systems are also processes that can introduce a lot of stress. "In-circuit" testers usually employ vacuum systems to hold down the board while pin contacts make contact with specific locations on the board. A rubber mat usually goes over the top of the board to allow the vacuum to work. Sometimes the fixturing is poorly designed. This can be a problem leading to excess flex stress on the board. One of the clues is to see the operator applying extra force by pressing on the rubber mat to help it make contact. This can increase the stress a lot, depending where fixture support pins are located. "Functional Testers," Burn-in Tests and Environmental Testers also are not immune. Most of these tests require the circuits to be accessed through the circuit connectors. If the volumes to be tested are large, the test engineer may automate the process of inserting the connector to the test fixture. The contact forces may be high, and the automation may overcompensate for these high forces. This fixturing must be looked at closely to make sure the boards are held adequately and that flexural stress does not occur as the board is inserted and also detached. The same concerns exist for manual connector insertion.

G. Cleaning equipment of various types all use some type of metal mesh conveyor to transport the boards through the cleaning medium. There is good opportunity for the boards to be caught in the mesh and to bend. If you have doubts, ask the equipment operator or maintenance people if they have ever found boards in the bottom of the cleaner. These probably caught on the mesh and were transported all the way around to the bottom. If this can happen, then it is possible that some boards are catching and releasing, bending the board, and applying flex stresses. There are many examples of excellent fixturing applied to the mesh conveyor and to the intermediate rollers at load and unload stations that help minimize these problems.

H. At final assembly, the board is finished, tested, and ready for installation in the final black box. This assembly process is usually thought of as easy and not worthy of much attention. Many of the new low-cost products have snap pins where the board is pushed on the pins and no other fastening is needed. Sometimes the placement of the board into the box requires some distortion. Look at all these with a careful eye. The final assembly operator might not be well trained in the hazards of electronic assembly.

I. With board assembly carriers, most high volume assembly processes utilize adjustable board carriers (boxes, etc.) to transport boards from one step in the process to the next. If these are not properly adjusted, the board can easily be flexed during insertion or removal. To correct this, make sure the carriers are properly adjusted for each board type.

J. Parts positioned in otherwise remote board locations can still be found to be failing with a flex crack. Finding the cause of these can require some complex detective work. The following are only a few of a long list of actual examples. The names have been eliminated to protect the innocent, or something like that:

1) Small board assembly into the finished product is not always easy. Sometimes the board must be placed over locating pins (see item H above), or sometimes the board must be placed into a connector and then on pins, or even into some housing cavity. Unless an automatic or fixtured assembly method is provided, the operator will find the "best" way. In one particular perplexing search, the entire process was reviewed. Except for some minor items, little was found that might cause the flex cracks that were occurring in customer returns. Finally, the product assembly process was looked at. The small board required assembly into a connector in the bottom of the housing, and then placed over two positioning "snap in" pins. The operator found the best process by bending the board, placing the board into the connector, and then snapping it into place. Ah ha! Once the assembly process was tooled to make this easy, the flex cracks disappeared.
Lesson: look at all processes.

2) In another difficult case, failures were occurring in locations down the centerline of the board. All of the processes were inspected — no luck. As a last resort, the wave solder process was looked at. Normally this is not a prime suspect, as failures do not happen until the part is secured in place by the solder. In this case a center roller on the "after solder" conveyor was misaligned and was higher than those on the edges. The board was warm enough, and the parts on the edges heavy enough that every board was bending along the centerline. The fix was easy. The roller was adjusted, and the failures disappeared.

3) In yet another case, parts were found to be failing in a "flex crack" mode in numerous locations all around the board. This did not fit the typical pattern. Detective work finally located the cause. The distribution of "heavy" components such as transformers, connectors, etc., on the board resulted in each board being twisted and warped after wave soldering. The operator was twisting them to get them near flat again. To correct this, fixturing to hold the board flat during wave soldering was added.

Proofs: The Root Cause was Found and the Solutions Worked

In some cases, the root cause is located, a solution incorporated, and it is obvious that it worked. In other cases, the root cause and the solution are not so straight- forward. There are some excellent tools to assist you in improving the odds. In reference 2, we learned about the use of strain gauges to measure the actual strain applied to the board during a particular operation. Since the investigation also determined the amount of strain needed to result in enough stress to cause flex cracks, this turns out to be a great tool to really pinpoint the root cause of the failures. It also really gives great confidence that your solution has worked. The only problem with the technique is that it requires some learning and trial and error in the art of using these fine strain gauges. KEMET participated in one of these studies with one of our most critical customers. It really works, and when the results are in, you can feel confident that you have nailed it down.

Black and White and Shades of Gray

Now that you have read all of the above, you might get the feeling that all the discussion of flex cracks is black and white. Good ..... that's how we wanted you to feel. Like all things that are positive, there is at least one exception. In this case, we have found that flex crack signatures can be found in board locations where it is really difficult to believe that flexural stresses were involved. In addition, these signatures happen on only one or two parts at the most. The failures are not repetitive. So we are left with a perplexing question. Since there are only one or two, how can we find the root cause? Since there are no likely flexural stresses, what could have been the cause of the failures?

We have a suggestion or two. First, we know that if a part is improperly removed from the board, a flex-like signature can be induced. Follow this scenario: One of the two solder joints is heated to melting, and the other end is not heated sufficiently. The part is then lifted from the board (as opposed to laterally pushed). This can result in a flex-like signature. The part is then returned for analysis, and the first conclusion is "flex crack". You can feel comfortable in knowing that when KEMET finds a flex crack signature, we do not assume it is the only cause of failure. We continue looking for another failure site and root cause, because we are concerned about how the part was removed (even when we do it). The worst thing that could occur is that the repair operator took the part off because the part was not aligned properly. Then the operator may have soldered the same part on the board. Capacitors are really inexpensive, and should be thrown away when removed from the board.

For the very rare cases -

- when there are only one or two failures,
- when it is impossible to locate a source of flexural stress,
- when the analysis is determined to be "flex crack,"
- we don't know either.

The End

Congratulations; you made it through this epistle. We, of course, are always interested in your comments. You know our objective is to work together to improve the overall process and give your customer the best possible product.

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