BGA Solder Joint Mechanical Risk Assessment during System Level Shock Test

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Abstract
The pressure to reduce overall form-factor size in the high volume chassis desktop market is driving the need to integrate components at the system level. Adding to the challenge of size reduction are pressures from increasingly shock sensitive active components, heavier heatsinks, lower cost targets, and decreased time to market. Integrating the system design was the logical step necessary to meet these challenges. However, with integration come complexities and dependencies that are difficult to optimally design, test, and troubleshoot. To evaluate these integrated chassis, classic engineering methods have been set aside in favor of newer innovative methods that can comprehend interdependent mechanisms. This paper will discuss overall system level design parameters that impact solder joint reliability performance and review the methods used to evaluate them.

Introduction
System level integration as a design concept was once reserved for ultra-complex main-frame computers, military, and aerospace, where dependability weighs heavy - has, by necessity, made its way to the desktop high volume market. Unlike those earlier users, the high volume desktop market places a high priority on keeping costs at a minimum. Lack of system integration familiarity is a major contributor to desktop designs not being robust, or restated, not comprehending all the sub-component interactions in the HVM desktop industry.

It is easy to understand that system design features (i.e. chassis, heatsinks, mounting locations, etc.,) significantly influence the motherboard dynamic response. The electronics industry produces substantial amounts of data for individual packages as they relate to board reliability concerns; however the missing piece to the puzzle is an understanding of the dynamic transfer function from the chassis through the circuit board to these shock sensitive components.

The challenge before us is two fold: (1) in an integrated system design, individual component interactions make it difficult to single out their contributions to the total system response, therefore a holistic system approach is necessary not one focused on each components contribution and (2) the need to examine these complex interactions calls for use of metrologies that have only recently been adopted in the desktop computer industry – namely board strain as a metric and high speed camera analysis to confirm global and local Printed Circuit Board (PCB) response. This requires us to first evaluate their applicability prior to their usage. The application and validation of these newly adopted tools will be discussed below. They were necessary to help unwrap the complexities of integration and also provide reliability assessments in a timely and cost effective fashion.

Finite element analysis is another effective tool for understanding design impacts, but has its own challenges such as non-linearity due to multiple interacting components, computing power demands, and development time. It is expected to become the tool of choice as time allows, but was left out for our evaluations.

This paper will describe a methodical approach that chassis designers can follow to identify critical system level design features that impact solder joint performance, and how to evaluate their impact.

System Overview
For this evaluation, key components that comprised *integrated* system are:

- Chassis: A folded steel housing of standard form factor with a volume of 13 to 30L. This includes an inner pan that contains the motherboard attach features.
- Mechanical Test Board (MTB): A non-functional but representative populated PCB.
- Support and Retention Module (SRM): A structural support plate under the PCB designed to uniformly dissipate inertial heatsink loads directly to the chassis.
- Thermal Mechanical Assembly (TMA): A large (~1200gm) thermal heatsink designed to create a comprehensive load on the solder joints of the socket and uniformly distribute inertial loads directly to the SRM.

Figure 1 is a diagram of a generic, *non-integrated* versus *integrated* system design highlighting the different load paths from the thermal solutions to the chassis.

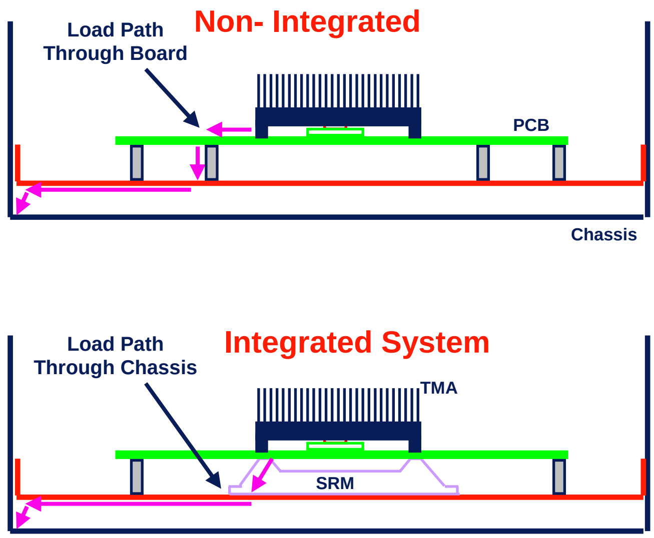

Figure 1 – Diagram of Non integrated vs. Integrated Chassis System Design

The classic *non-integrated* chassis have thermal solutions supported exclusively by the PCB. These designs are typically restricted to lower powered microprocessors that can be cooled with heatsinks weighing less than 550gms or else driven to more expensive liquid/heatpipe solutions. On the other hand, an *integrated* design that is connected directly to the chassis (and may include stiffeners) have no such limit to their thermal solutions and can support high wattage microprocessors.

Discovery - Chassis Dependency on Solder Joint Cracks

During initial industry validation of the first generation integrated chassis, it was discovered that some chassis designs yielded a greater number of solder joint cracks to key components (see Figure 2).

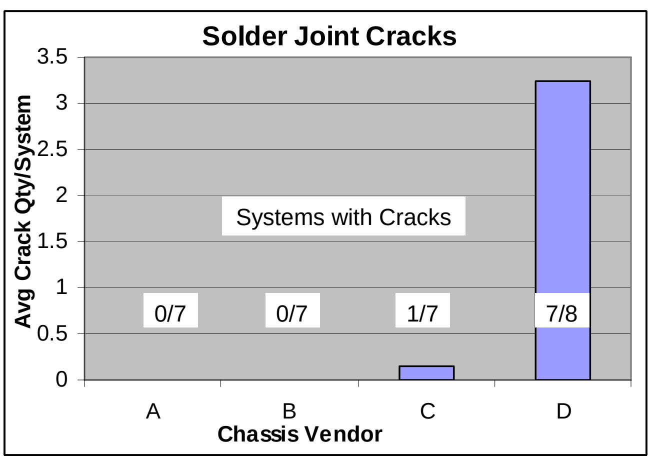

Figure 2 - Chassis Vendor Variation Measured by Solder Joint Cracks

Given all the chassis were equipped with structurally identical critical components (SRM, PCB, TMA) it was concluded that the variation in the quantity of observed cracks had to be linked to subtle differences in chassis design features. The concern was how we can detect these subtle chassis design features. This required newer metrologies and methods than just visual inspection.

Establishment of Metrologies – Board Strain

Before embarking on the path to root cause of these cracks, it was necessary to establish a metric to assess solder joint risk. Although measuring crack severity through a dye-stain then peel or cross-section process is the most direct and indicative measure, it unfortunately is quite costly and slow. This lead us to investigate a relatively new metrology to the desktop PC world – measuring the board strain with strain gages during a shock event on the bottom-side of the PCB directly under the point of concern [2]. This is illustrated graphically below in Figure 3.

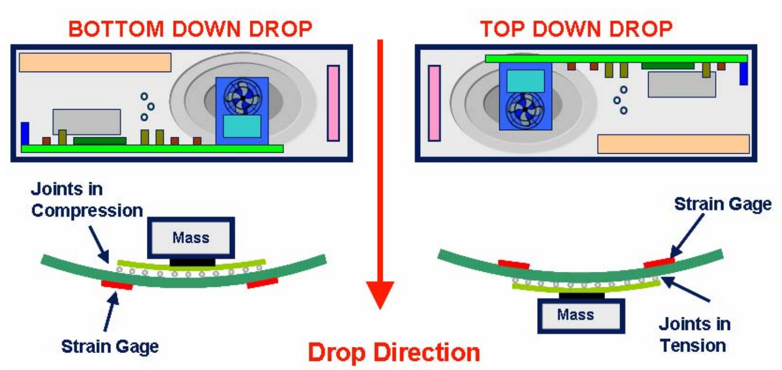

Figure 3 - System Drop Orientation Relative to Strain Gage Mounting Location

In this case, the critical point is the corner joints of the Ball Grid Array (BGA) components. But before accepting board strain as a metrology, we first need to be convinced that board strain is a valid indirect measurement of solder joint crack(s).

To build this relationship between board strain and solder joint cracks, systems from multiple vendors were similarly configured and drop shocked as before. To increase the solder joint crack signal the critical BGA components were subjected to 2 extra package only reflows prior to assembly onto the board to cause greater susceptibility to solder joint cracking. The test results are shown below in Figure 4.

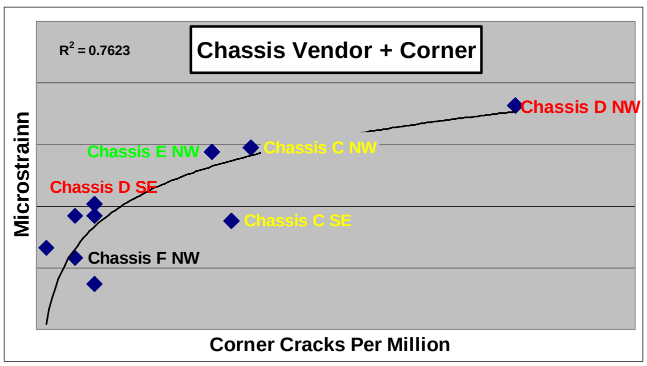

Figure 4 – Strain to Crack Correlation

Figure 4 shows that the BGA corners that received the highest board strain had the highest solder joint failure rate. Figure 5 illustrates how sensitive the strain gages are by showing the associated board strain at each corner of the BGA. Here you can see (as in Figure 4) that the NW BGA corner produced the highest strain and highest number of crack observations.

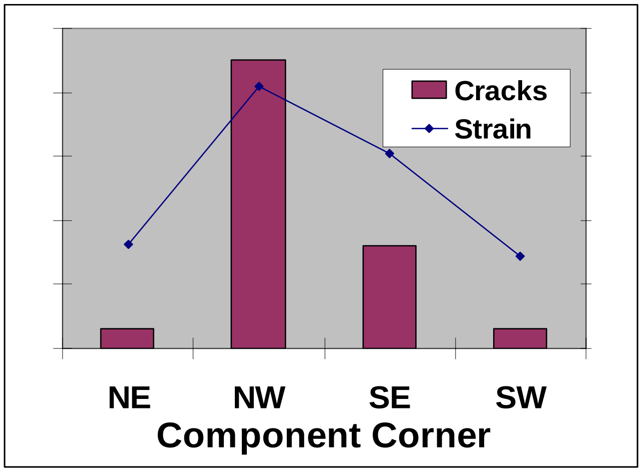

Figure 5 – Correlation between Amount of Solder Cracking and Board Strains at the Same Corner

With a link established between strain and solder joint cracks, an inexpensive and relatively quick metrology to locate areas of potential design flaws is available. When correlated to acceptable solder joint quality standards it can establish a measurable limit that ensures new designs meet solder joint reliability concerns. This also helps to decrease time to market as well as the number of design revisions required.

Establishment of Metrologies – High Speed Camera

To aid in exploratory investigation and bolster any conclusions, it was agreed to employ a high speed camera. A high speed camera when matched to compatible software can produce a topographical out of plane displacement map during the most severe moment in a simulated shock event. That map can then be superimposed over an actual motherboard image to give insight to localized responses, see Figure 6. The radius of curvature is smallest (worst) where the gradient line spacing is closest. The component's NW corner is labeled and lies near one of the most aggressive transition zones (highest bend curvature = highest solder joint stress).

A quick evaluation of the board surface from a global view confirmed excessive bending at the NW corner of the BGA in question. This offers another confirmation that board strain (board curvature) is an indicator of solder joint health (or stress). It also illustrates a high speed camera can non-destructively provide credible insight as to what happens during the shock event.

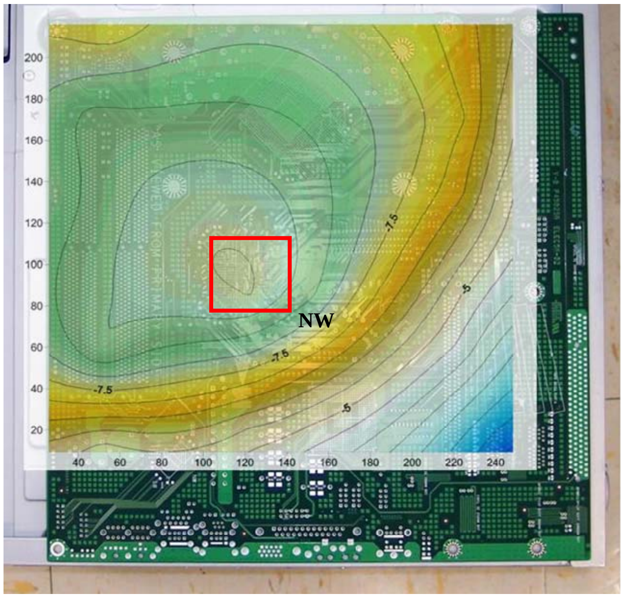

Figure 6 - High Speed Camera Topographical Out-of-plane Displacement Map Superimposed over an Actual Motherboard

Now that the metrologies have been established, the focus is now directed to chassis investigation and design features that affect solder joint reliability.

Chassis Design Feature Observations

Before devoting resources to investigating specific parameters, a generic survey of chassis characteristics across multiple vendors was compiled and the results are summarized below. Tying the mechanical differences to the change in response can give indications to where to look first.

- Inner pan thickness - since material cost makes up a large portion of chassis costs, vendors try to optimize where possible. Obviously metal thickness can have a big impact on cost. The chassis thickness observed ranged from 0.6 to 1.0mm.
- Inner pan elevation – smaller chassis can have an inner pan contact the outer cosmetic pan. The dimension of the outer chassis pan is the primary driver for the need to elevate the inner pan. In order to ensure the front vanity panel i.e. the most visible feature of the chassis is symmetrical, the inner pan must be raised in order to center the fan.
- Embossing – adding these structural impression into the pan increases rigidity to the inner pan. The resulting ribs on the perimeter of the embossment provide shear support for direct loads. Embossing depths range from 0 to 5mm and most span 2/3 of the chassis width. See Figure 7 for an example.

Figure 7 - Example of Chassis embossing

- Other features – other difference noticed that were noticed that could potentially change the structural integrity were :method of attaching the inner pan to the cosmetic outer pan through rivets, screws, or even no attachments, added folds that provide support similar as embossing, and the perimeter folded edge wherein the inner pan travels up (or down) the outer cosmetic sides.

Figure 8 below gives a conceptual description of chassis features mentioned above.

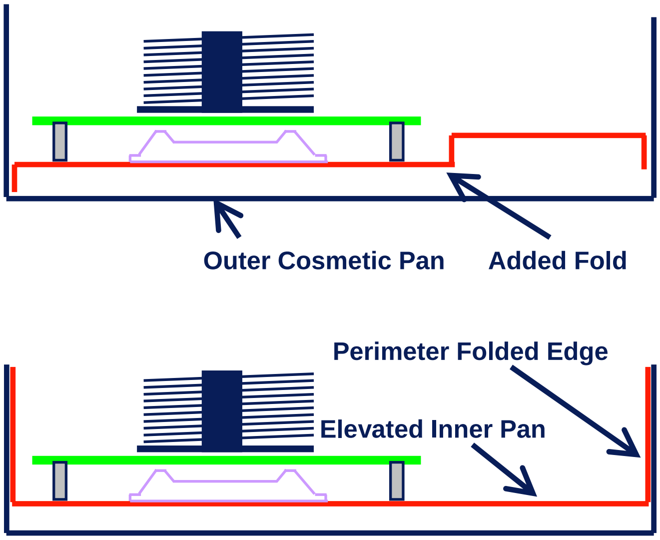

Figure 8 - Conceptual Description of Chassis Features

Investigation of Chassis Stiffness and Corresponding Parameters

It was assumed that the inner pan stiffness strongly dominates in the dynamic shock transfer function from the chassis to the component. It was decided to measure the load/deflection on the differing chassis; compare it to measured board strains and the observations mentioned previously; then check for correlations.

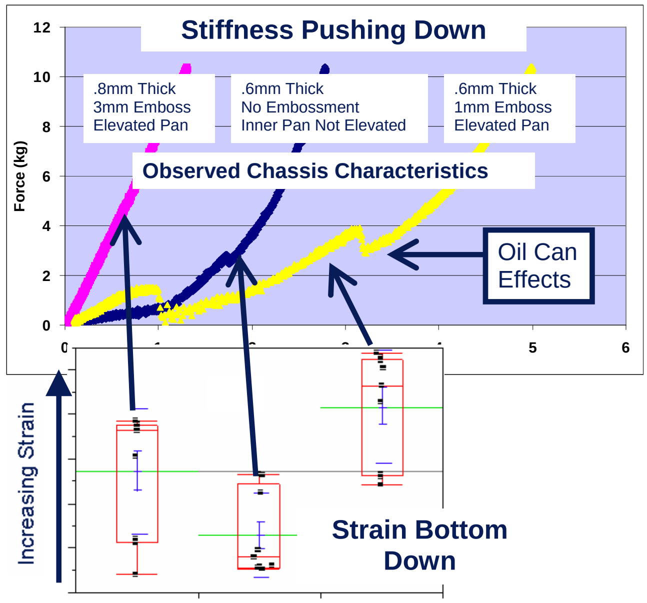

Figure 9 - Correlation of Board Strain (lower graph) to Force Deflection of the Three Chassis Evaluated

The graph in Figure 9 shows the board strain condition from a drop shock in the chassis bottom down configuration placing the BGA solder joints in compression; reference Figure 3 for chassis orientation. This corresponds to a “push down” on the chassis pan and is representative of the loading condition simulated in the force deflection graph shown in the upper part of the Figure 9. There are several observations on the graph that are worth noting:

- For the leftmost line (magenta) is the stiffest of the three chassis. The benefits of a thicker pan and embossing are immediately recognized due to the undisturbed linearity of the load vs. displacement trace carrying all the way through until the end of the test. It should also be pointed out that no “oil can” effect (caused by snapping through concave to convex = non-linearity) was measured with this configuration but was detected in the two remaining chassis.
- The center chassis (blue) appears to be less stiff compared to the chassis on the left (from 0 to 6 kg). It was noted that the soft or flimsy chassis response in this region was due to the inner pan displacing until it makes solid contact with the outer cosmetic pan to eventually provide an overall effective stiffness similar to the first chassis tested on the left. This effect can be seen in the load-deflection curve slope being similar to the chassis on the left. Interesting to note is this chassis produced the lowest board strain.
- The rightmost line (yellow) represents the worst of all conditions. This is attributed to the low width-height embossing and a thinner pan material. As expected, the highest board strains are also observed.

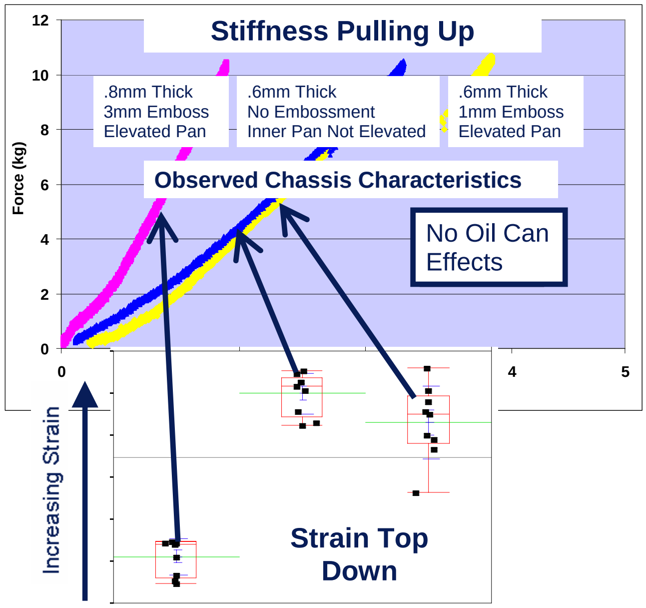

Figure 10 – Correlation of Board Strain (lower graph) to Force Deflection – Top Down Condition

When you flip the chassis over, this places the solder joints in tension and presents a test condition that is worthy of discussion and comparison to the bottom down orientation just mentioned. A similar graph to that in Figure 9 is presented in Figure 10 for this chassis orientation.

The interesting observation in the above data is that when pulling up, the benefits of the non-elevated inner pan chassis is lost, and its stiffness and lower strain values are not realized. It is assumed that the chassis will be dropped in the orientation illustrated in Figure 9 more than in Figure 10. For this reason chassis designers have focused on stiffening up the “bottom” of the chassis. This holds true for when a computer is in its shipping container but is no guarantee that those delivering the computer will religiously keep the package in its marked “up” position during shipping. So both chassis orientations should be investigated.

It should be mentioned here that the four other orientations (X+, X-, Y+, and Y-) were also tested and monitored for strain response and deemed benign as a significant contributor to solder joint failure.

Finding a Measurable Limit

The preceding data illustrates a simple but effective indirect measurement method (force/deflection) by which chassis designer can check the structural soundness of their chassis. The missing piece and what will be discussed next, is how to define a minimum threshold of stiffness that will prevent solder joint failure.

Finding the critical stiffness value required a method to vary the stiffness in a controlled manner. Having the inner pan manufactured during a press-form process prevented the feasibility to perform a study of embossing depths and designs – since new dies are prohibitively expensive. It also was not practical to consider using separate vendors to represent varying stiffness since other chassis feature differences introduce noise factors that cannot be filtered out. It was decided instead to simulate the effects of changes in stiffness by epoxying and riveting a hat channel of equivalent mass and thickness, but varying depths, to a chassis with a known weak inner pan. Hat channel geometries are shown in Figure 11.

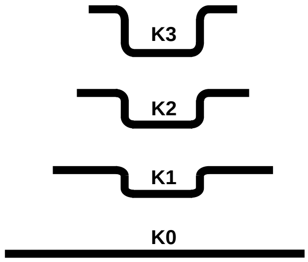

Figure 11 - Hat Channel Geometries Evaluated

The effect of the hat stiffeners are shown in Figure 12 when the chassis was drop shocked to a common test condition. The graph does confirm the relationship between stiffness on the inner chassis pan as measured by the strain gage underneath the BGA component in the top down and bottom down condition. For both tension and compression the hat stiffness seems to reach a maximum effectiveness with the K2 stiffener.

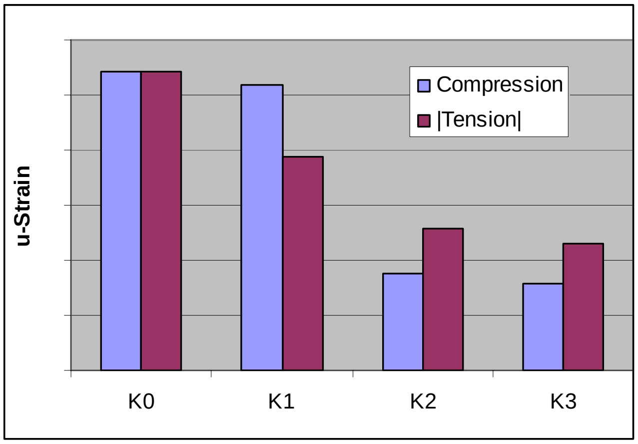

Figure 12 - Effect of Hat Stiffeners on a Common Chassis as Measured at the BGA

To determine the critical stiffness value, we need only to draw a (sloped) line representing stiffness vs. strain being intersected horizontally with a line that represents the board strain at which the component starts to fail. The stiffness value at that intersection dictates the critical design stiffness that should not be exceeded. An illustration of a critical stiffness design graph is shown in Figure 13.

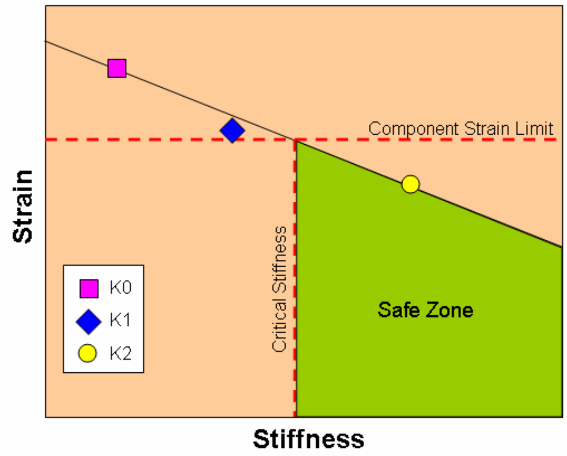

Figure 13 - An illustration of a Critical Stiffness Design Graph

It is left to the designer on the arrangement of chassis features used to achieve the minimum stiffness. However the following discussion about the known parameters effects can provide a head start down the path of a successful design.

Recommendations to Improve Chassis Stiffness

Embossing: Embossing, when designed properly, provides support across the span of the chassis. This support helps keep the mass of the TMA/SRM combination from moving independent of the chassis. It also helps to prevent the "oil canning" phenomenon that increases overall board displacement during shock. The embossing impression depths of 1mm or less did not provide a noticeable difference in response.

The placement of the hat stiffener is also a consideration. Generally speaking a desktop size computer would have a minimum of two hat stiffeners: one under the SRM and one near the center of the board, run perpendicular to the long axis of the SRM, and span from sidewall-to-sidewall where possible.

Sheet Metal Thickness: Unlike embossing, which is a one-time engineering and tooling cost, sheet metal thickness is an incremental cost vendors do not want to incur. It is perhaps possible to design with thinner gauge metals if other clever support features are added or material specification is changed.

Inner Pan Sidewall Attach Method: Increasing surface tension is another contributor to overall pan stiffness. If the full perimeter of the chassis can be solidly attached to the sidewalls, the tension (like a drum head) will help resist deflection. Typically the edges of the thinner pan are folded then riveted to the sidewalls.

It was observed that some chassis developed an "oil-can" effect after shock even that was not previously present. Root cause was traced back to the plastic deformation at the immediate area surrounding the rivet head. A paired study using the as-built 150mm pitched rivets against a chassis augmented to a 25mm spacing was tested to understand the effects (see Figure 14 below). The results of the chassis study are shown in Figure 15.

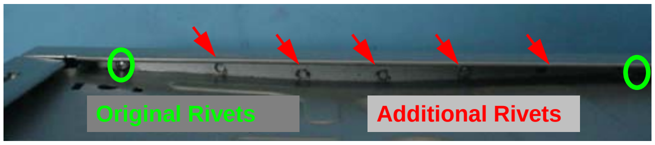

Figure 14 - Attachment between the Side Wall and Inner Pan

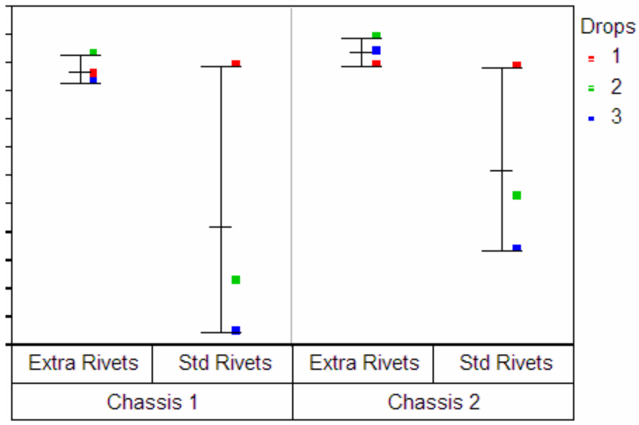

Figure 15 – Rivets affects on Board Strain

Notice that there was no difference observed between the initial (in red) drop using the standard rivet spacing and the drop with the extra rivets for the first drop. But there is substantial drop in capability for subsequent drops. If field conditions were limited to one dynamic event during shipping no issues would arise. But in the real world this chassis would be less rigid or "loose" after one drop and render itself susceptible to solder joint failure.

This data indicates that rivet spacing has a minimum requirement tied to the material properties of the sheet metal used. It is recommended that rivet spacing be held to a feasible minimum pitch to help ensure loads do not drive the sheet metal to plastic deformation.

Folded Edge: It is evident from Figure 14 above that the pan shape has plastically deformed. The actual displacement measured is 2.4mm. To help prevent this, the folded edge of the inner pan edges could be increased. However, the fold would have to be reversed from the one pictured since the length of the fold would be limited by the pan elevation in its current configuration.

Additional System Parameters that can Protect Solder Joints

Stiffening the pan goes a long way to improving the survivability of solder joints in key components during a shock event. There is no guarantee of system success without attention to other design features meeting some level of minimum standards. Engineering brainstorming sessions and high speed camera data reviews led insight into other chassis parameter interactions.

TMA Stiffness: A key role that the Socket thermal solution plays is to prevent solder joint failure by loading the Socket enough to keep the joints in compression. In this particular design it does that quite well, which is evident by the lack of solder joint failures detected. However, the loading does bend the boards which causes a secondary impact to the surrounding components and gets exacerbated by a shock condition. To dampen the effect the large mass of the Socket heatsink has on the surrounding components, the heatsink can be designed in a manner that uses a TMA to direct the inertial load directly to the SRM rather than through the Socket. Figure 16 below shows TMA drawings for three different designs that were investigated and their corresponding effects on board strains at the neighboring BGA component in what is considered the weakest chassis.

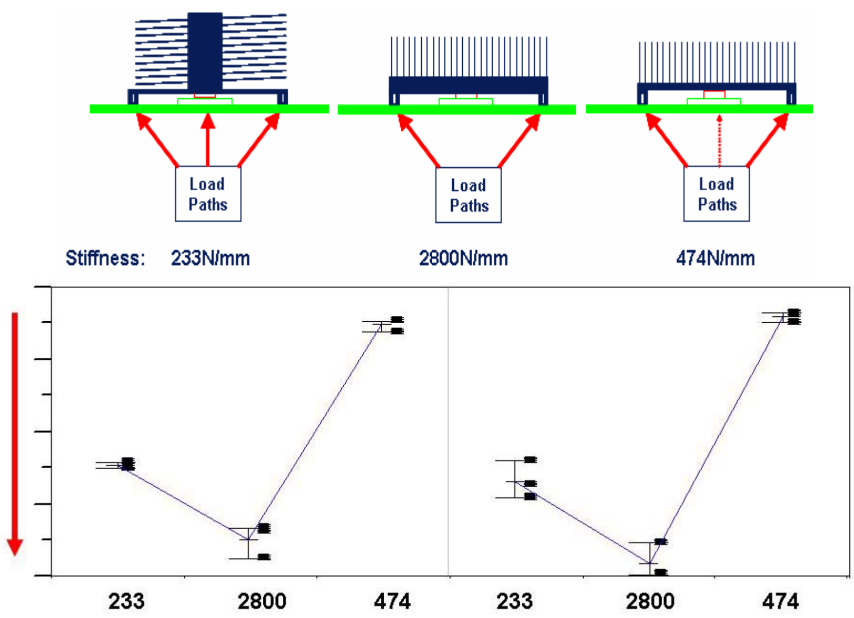

Figure 16 - Three Variations of TMA Evaluated

The TMA influence was enough to justify a minimum stiffness of the thermal solution. Similar to the design approach for the critical stiffness described previously a design envelope was produced for the TMA stiffness, Figure 17.

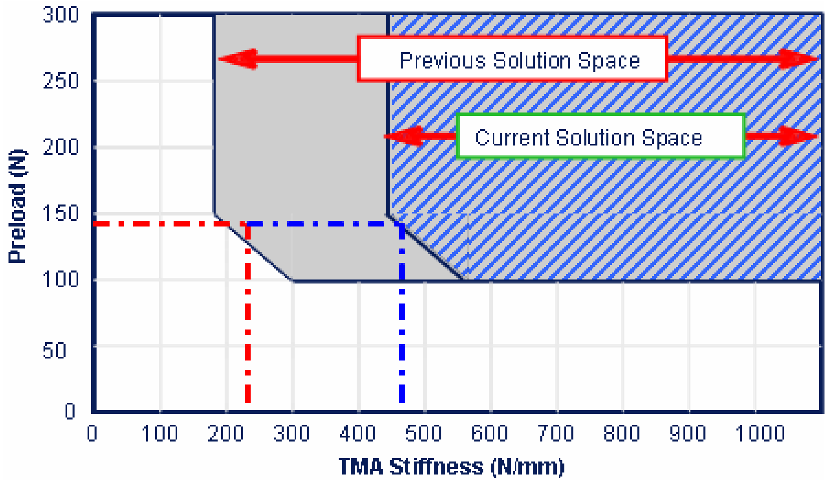

Figure 17 - TMA Stiffness Design Envelope

BGA Wave Solder Heatsink: For the components that do not require a 200+ gm heatsink a thermal solution that is soldered to the board can provide added protection if required by providing localized stiffness. This solution is a cost adder to the more prevalent Z-clip or anchor solution typically used but provides an added measure of solder joint protection.

Stand-offs: For the most part, the methods used to connect and elevate the board from the chassis pan provide equal and adequate protection. Though one particular design resulted in adverse conditions, it was a cantilevered bridge lance mounting and is illustrated below in Figure 18.

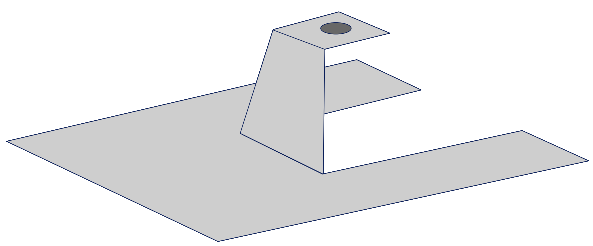

Figure 18 – Cantilevered Bridge Lance Stand-off

Snubbers: Well placed snubbers (rubber bumpers) can be very useful in controlling board and inner pan displacement. For maximum effectiveness they need to control both compressive and tensile movement. Since the placement is dependent on the chassis design it is not practical to provide recommended generic locations.

Conclusions

The pressure to reduce form-factor size is driving the need to integrate components at system level in high volume desktop PC market. However, the lack of system integration familiarity and the pressures to keep costs at a minimum has truly challenged the desktop chassis manufacturers.

The initial industry validation of first generation integrated chassis showed varied solder joint cracking. Prior to attempting root cause to this varied solder cracking behavior across multiple chassis, it was necessary to establish metrologies to assess solder joint risk. Newer metrologies such as board strain and technologies such as high speed camera were utilized for this assessment. A strong correlation was observed between BGA corners that received highest board strain and highest solder joint cracking. Additionally, a high speed camera experiment was performed to confirm the above correlation. Once the metrologies were defined, the focus was directed towards chassis design features.

A generic survey of chassis characteristics such as inner pan thickness/elevation, embossing, etc., was conducted across multiple chassis vendors with the objective of tying mechanical differences to change in solder joint crack response. The load/deflection (stiffness) experiments helped correlate inner pan stiffness to the observed BGA board strains. This simple and effective stiffness experiment can help chassis designers to check for the structural soundness of their chassis.

The next critical item was to define a minimum threshold of stiffness that would prevent solder joint failure. This required experimenting with various hat stiffeners to modulate the stiffness of the inner chassis pan. A clear relationship between pan stiffness and BGA microstrains was demonstrated via a critical stiffness design graph. Chassis designers can use this graph to ensure the minimum stiffness requirements are met. Also, several recommendations to improve chassis stiffness and system design were provided to aid designers in meeting the above requirement.

This paper has described a methodical approach that chassis designers can follow to identify and evaluate critical chassis design features that impacts solder joint performance.

Acknowledgements
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