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Forensic Engineering Analysis of Design & Manufacturing Practices for an Automotive Spring

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Abstract

A child fatality case focused on the failure of springs in an automotive control system switch. In the forensic engineering analysis, the actions of the spring manufacturer, switch manufacturer, control system manufacturer, and vehicle manufacturer were of interest. Relevant details included the spring manufacturing drawing, the spring design itself, the Design Failure Modes & Effects Analysis (DFMEA) conducted by the switch manufacturer, apparent absence of quality assurance testing, warranty return failure descriptions, and the actions taken by various entities upon notice of spring failures.

Keywords

Forensic engineering, spring, FMEA, fatigue, validation, quality assurance, control, warranty

Introduction

A child was playing unattended in the cab of a mid-2000s model year vehicle. When the child turned the ignition key, the engine started, and the vehicle rolled forward — striking a toddler playing outside the vehicle. A post-incident inspection revealed that the vehicle could be started without engaging a particular control switch intended to preclude vehicle starting unless the switch was engaged. Further, the inspection revealed that the switch likely jammed in the engaged position due to the failure of compression springs used in the switch. Optical and Scanning-Electron Microscopy (SEM) revealed that the failed spring coils had numerous torsional fatigue fractures, and some regions of the broken spring wire exhibited longitudinal radial cracks that may have acted as stress raisers.

In this case, the following parties were named as defendants (actual company names have been changed): vehicle manufacturer "Alpha," vehicle control system manufacturer "Baker," control switch manufacturer "Crown," spring manufacturer "Delmar," spring wire manufacturer "Echo." Vehicle manufacturer Alpha created performance specifications for the control system. Control system manufacturer Baker subcontracted the control switch design and manufacture to Crown. In turn, Crown created the spring design drawing and production specifications as part of the switch design, and contracted with Delmar to produce the spring. The batch of wire used by Delmar for the subject springs was made by Echo.

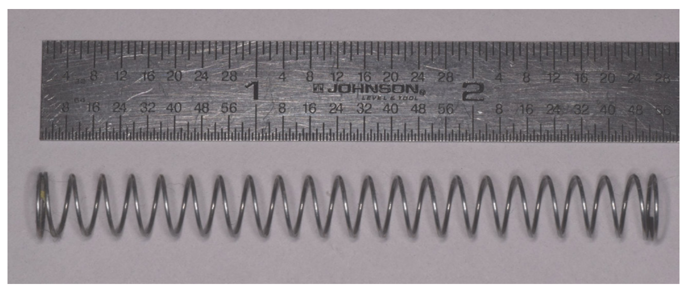

Figure 1
Exemplar compression spring.

The switch was designed to compress two identical parallel springs in a nominally axial manner during control engagement, and the springs return the switch to a non-engaged position once the control is released (**Figure 1**).

The subject spring was designed by Crown and released at revision A in the late 1990s. The design data on the revision A manufacturing drawing, created by Crown, is shown in **Figure 2**. Values have been changed slightly for confidentiality:

Analysis and Findings

<u>Spring manufacturer "Delmar"</u>

- Spring manufacturer Delmar was not involved in the design decisions or risk evaluations pertaining to the spring or its use in the control switch.

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	Nominal value	Tolerance	"Critical" dimension	SPC sampled
Spring length	2.85"	+/- 0.025"		
Coil outside diameter	0.270"	+/- 0.004"		
Number of active coils	20			
Total number of coils	22			
Wire diameter	.018	+/- 0.0005"		
Wire material	Music wire			
Wire plating	Tin			
Load at 1.85" compressed length	0.50 lbf	+/- 8%	•	•
Load at 0.470" compressed length	1.30 lbf	+/- 12%	•	•
Maximum solid height	0.440"		•	

Figure 2
Design data from spring manufacturing drawing.

The testimony and discovery materials reviewed were consistent with this.
- Delmar did not participate in the design of the spring or the switch.
- Delmar had no substantive understanding of the safety risks inherent in the spring application — they knew only that it was for an automotive application.
- Delmar had no contractual obligations to track the performance of springs in use.

- Given the information Delmar was provided by Crown, it was reasonable of Delmar to rely upon (and not question) Crown's spring design information, based on Crown's position as a large "Tier 1" manufacturer of automotive components that Crown sold directly to automobile manufacturers.
  - Delmar's president stated in his deposition that the company would get complete drawings from Crown and manufacture springs in accordance with the drawing. There was no need for further design work.

- Delmar produced the spring using processes typical to the spring manufacturing industry and in compliance with Crown requirements.
  - Material control: Delmar used matched work order tickets to associate individual wire coils with specific jobs. Discrepant materials were quarantined pending resolution.
  - Sampling:
    - Delmar did a full dimensional analysis of Crown-designated spring dimensions and loads during the setup of each production run as well as at the end of the run.
    - During production, Delmar would check the three Crown-specified critical measurements (solid height, minimum and maximum loads) on a minimum of 12 samples per day — or more, if needed, to meet the sample quantity for Crown's "zero acceptance*" requirement chart.
    - Delmar prepared a capability analysis of the load measurements from samples, using Statistical Process Control (SPC) data. SPC data in the form of "X-bar & R" charts were provided with every order.
    - Delmar was not required to inspect every spring; nevertheless, the spring forming machine utilized a noncontact sensor to verify that each spring's free length fell within the specified tolerance (**Figures 3** and **4**). A significant variation in material condition or machine

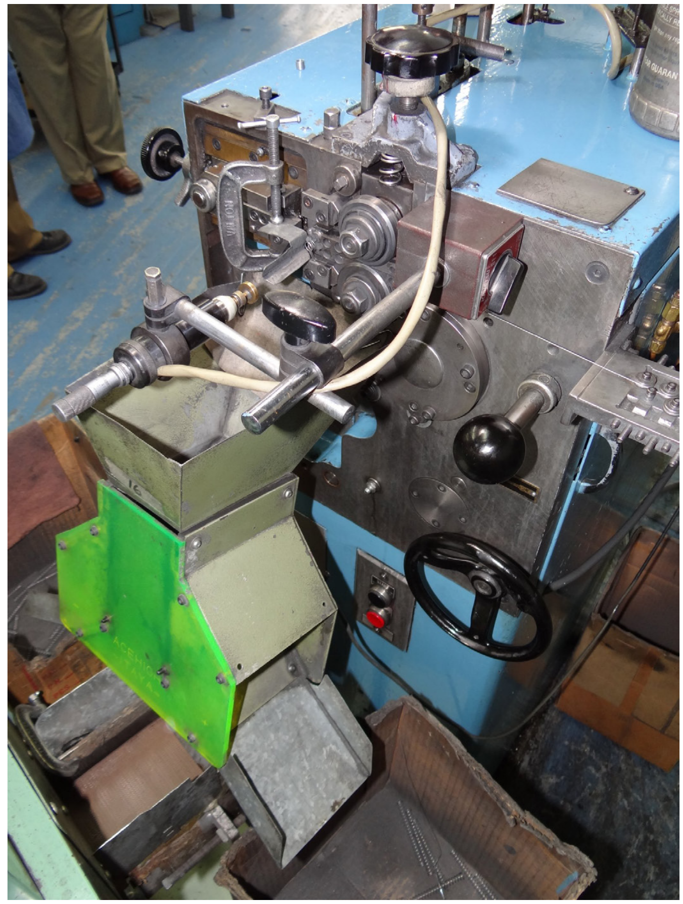

Figure 3
Spring forming machine.

* The term "zero acceptance" refers to quality assurance methodologies utilizing an acceptable quality limit in conjunction with a chart that establishes how many samples must be measured, depending upon manufacturing lot size. If one defect is found among the specified number of samples measured, the entire lot is rejected (i.e., zero are accepted).

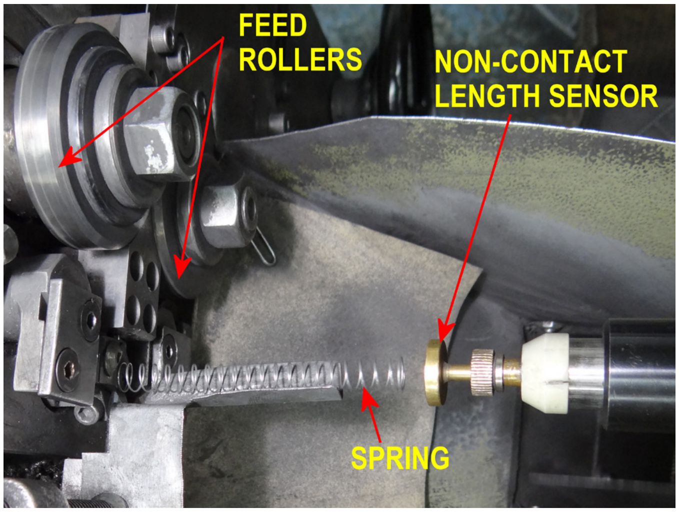

Figure 4
Feed rollers and length sensor.

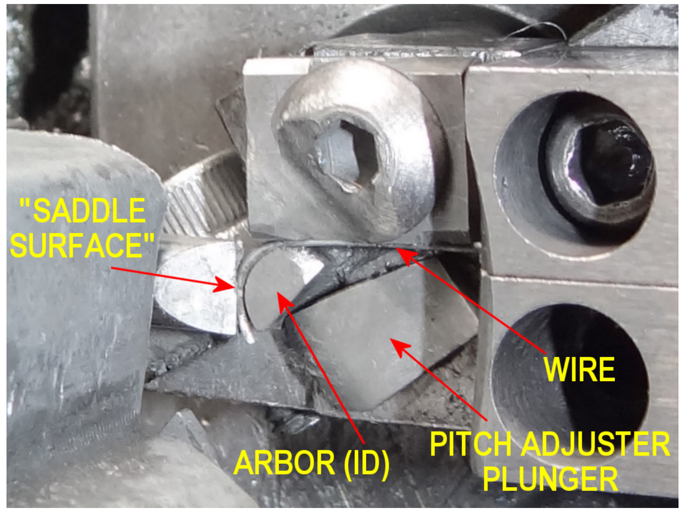

Figure 5
Spring forming surfaces.

performance would cause an out-of-tolerance free length, and the spring would automatically be rejected to a scrap bin. The spring forming machine was set up to automatically adjust itself to correct for the rejected spring's free length discrepancy, on the next spring made.

  - The use of sampling is common in mass production of inexpensive parts such as the spring; the subject spring had a production price of $0.03.

- Delmar utilized a typical type of spring forming machine, in which the spring coils are formed through a "wiping" plastic deformation; the coils are not formed by "rolling" plastic deformation. As such, the surface of the wire will exhibit some damage due to localized galling and abrasion of the wire where it rubs the concave "saddle surface" of the spring forming machine, during plastic deformation (**Figure 5**). Additionally, there was an opportunity for minor flattening of the spring wire as it went through the forming machine's feed rollers (**Figure 6**).

• In the litigation, it was asserted by other experts that Delmar was the responsible entity for the fatigue failures, due to the radial cracking of certain portions of the spring wire. Some of this radial cracking was observed to be originating from the "center" of the flattened area of the wire, and some was observed to originate from the galled/abraded area of the wire surface inherent in the forming process. See **Figure 7** for a simplified representation of the cracking. Note that not all fatigue failures showed evidence of this radial cracking in the wire.

• It was asserted by other experts as well that some of the longitudinal radial cracking was found to have slight amounts of tin present within the cracks near the wire surface. In turn, these experts asserted that the wire was improperly manufactured by Echo and improperly inspected

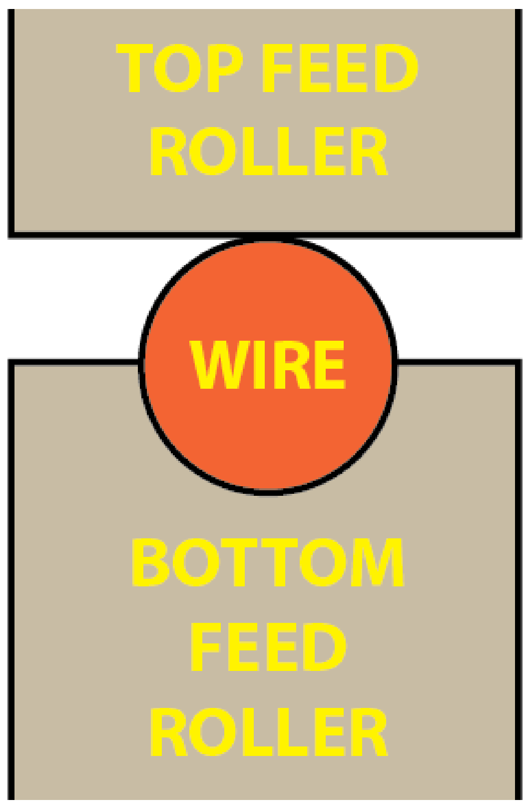

Figure 6
Feed roller configuration.

by Delmar. It was later revealed that Delmar's normal post-forming stress-relieving process, in which the spring is baked to relieve internal stresses, was done at an industry-accepted temperature that happened to be above the melting point for tin. As such, it was possible that surface tin plating wicked into some of the longitudinal cracks during stress-relieving. Regardless, Delmar had no contractual requirement to conduct any microscopic evaluation of Crown's springs or of its incoming spring wire material. The company manufactured the springs for years before any failure concerns were brought to its attention.

Control switch manufacturer "Crown"

- As the designers of the subject spring, Crown failed (in the opinion of the author) to appropriately analyze the safety risks associated with using the spring in its control switches.
  - A Crown engineer conducted a Design Failure Modes & Effects Analysis (DFMEA) for the switch during the spring's design in the late 1990s. This DFMEA document formed the basic safety risk analysis for the switch, given the requirements of Alpha's performance specification. FMEA, in general, was first used in the automotive industry in the 1970s; there are variants, including Process FMEA for manufacturing and FMECA (Failure Modes, Effects, and Criticality Analysis). The purposes of a DFMEA were described in Society of Automotive Engineers (SAE) *Recommended Practice J1739-1994*, an FMEA reference manual jointly developed by U.S. vehicle manufacturers and first published in 1994[1]. It was the current version of J1739 when the DFMEA for this spring design was completed; J1739 was most recently revised in 2009.
    - Per Section 1.1 of J1739-1994: *"An FMEA can be described as a systemized group of activities intended to: (a) recognize and evaluate the potential failure of a product/process and its effects, (b) identify actions which could eliminate or reduce the chance of the potential failure occurring, and (c) document the process."*
    - Per Section 3.1 of J1739-1994: *"In its most rigorous form, an FMEA is a summary of an engineer's and the team's thoughts (including an analysis of items that could go wrong based on experience and past concerns) as a component, subsystem, or system is designed. This systematic approach parallels, formalizes, and documents the mental disciplines that an engineer normally goes through in any design process."*
    - Per Section 3.1.2 of J1739-1994: *"During the initial design potential FMEA process, the responsible engineer is expected to directly and actively involve representatives from all affected areas. These areas should include, but are not limited to: assembly, manufacturing, materials, quality, service, and suppliers, as well as the design area responsible for the next assembly."*
    - The FMEA methodology provides a framework, but the outcome entirely depends upon proactive consideration and contemplation by the responsible engineer and production team.

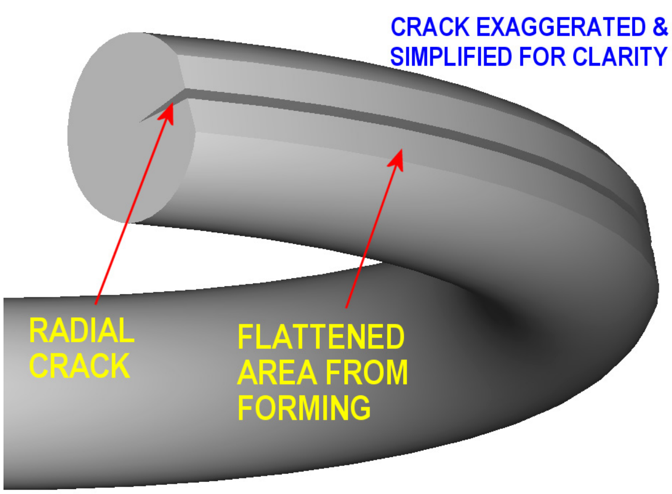

Figure 7
Radial cracking.

  - For a particular potential failure cause and associated effect, a DFMEA involves the engineer & team's appraisal of the severity of the effect and the likelihood of occurrence of the cause. For prioritizing risk mitigation, there is also the factor of detection. In SAE J1739, detection pertains to whether design controls should detect the cause or failure mode before the design is put into production. Design controls may include validation testing, engineering studies, field testing, etc. In the case of the Crown DFMEA, however, comparison with an earlier Crown DFMEA for a similar switch reveals that detection was apparently expected to be done by the end-user. It is reasonable to compare these early and late 1990s DFMEA documents, as they shared identical content for the DFMEA analysis pertaining to the subject failure effect, which was "vehicle starts regardless of the switch position." Identical as well between the old and new documents were the severity, likelihood, and detection ratings — it is unknown whether the Crown engineer properly evaluated this new switch and its new spring design, or simply copied this section in its entirety from the previous DFMEA. The severity rating assigned by the Crown engineer for the failure effect was "hazardous-without warning" — an appropriate choice. The likelihood of occurrence and detection ratings, however, were both "remote." As the DFMEA engineer, he should have had a basis for deciding these causes were unlikely — perhaps he was assuming that specific design controls would be used, and that they would be effective.

- The three potential failure causes included: 1) "debris in the switch;" 2) "broken components in the switch;" and 3) the subject springs were weak, absent, or damaged. Regarding this last potential failure cause, the design controls (i.e., the solution, in theory) were:

  - The spring supplier would incorporate SPC during production. (Author comment: This presupposes SPC will capture all relevant defects, and does not establish which spring feature dimensions are critical.)
  - A periodic sample of the springs would be checked for proper forces and defects at incoming inspection, and each completed switch would be tested for circuit isolation. (Author comment: It is likely that one of these switches could have a missing spring and still pass circuit isolation, though this wasn't tested.)

- Among the three failure causes, the author noted there was no mention of fatigue failure of the springs — one of the most important considerations in using springs for high-cycle dynamic applications. Further, none of the design controls outlined for preventing this catastrophic failure effect do anything to predict or detect spring fatigue. One of the most obvious sources of potential failure in a critical dynamic spring application was not even addressed in Crown's DFMEA for the switch.
- It is particularly ironic that fatigue was not addressed as a potential failure cause for the main switch springs because fatigue was addressed as a potential failure cause for the switch's electrical contact components, under the failure mode "vehicle fails to start." The design controls in place were that the switches must meet Alpha validation tests and that there was to be continuous production line durability testing.
- One could assert that if the electrical contact components undergo durability testing, then the subject springs would "come along for the ride" and be tested as well. But such indirect testing is not the hallmark of a thorough DFMEA, in the author's opinion. Regardless, in a properly-conducted DFMEA, design controls are an integral element of the product's overall validation and control plan. Beyond the discussion of the requirements in the Alpha performance specification, the design controls "inherited" by the springs included ongoing production line durability testing. Such controls can be effective (if practiced).

- Spring design
  - Most of the entities involved in the case (including both manufacturers and experts) had relied at some point upon spring design software sold by The Spring Manufacturer Institute, and currently known as "Advanced Spring Design" (ASD). This software is based on TK Solver from Universal Technical Systems (Loves Park, IL), and version 7.13 was used by the author. Using this software, the spring design created by Crown theoretically had an acceptable fatigue life, using the nominal print dimensional values. However, in the author's opinion, the spring was a marginal design with issues that necessitated higher levels of design control, durability testing, manufacturing quality control, and warranty oversight than were practiced by Crown.
  - Crown's chosen print dimensions did not result in a spring that reached the nominal specified load magnitudes; if the print-specified geometry AND loads are input into the ASD software, it returns an "inconsistent" warning.
  - To meet the print, if a supplier such as Delmar is adjusting its spring manufacturing machine to target these median loads (as the loads are

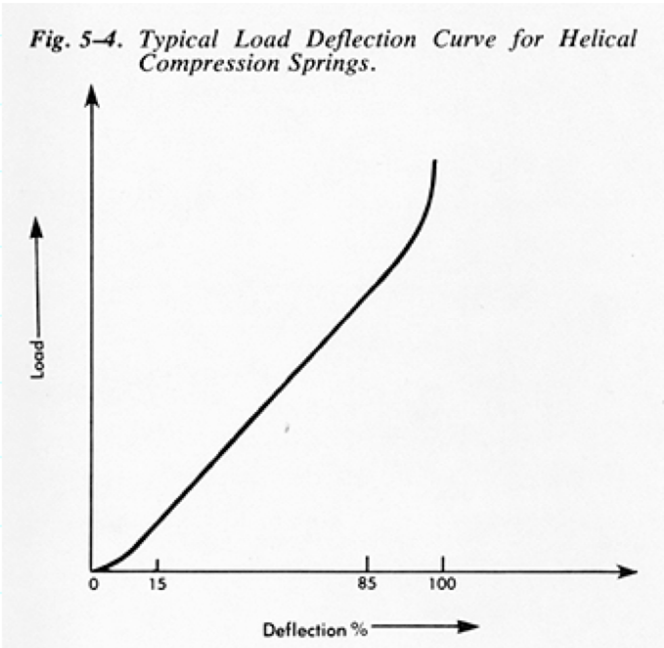

Figure 8
Load deflection versus load magnitude.

monitored through SPC), the machine operator must "juggle" other spring design factors within the tolerance bounds established on the print. If the spring design parameters input into ASD software are focused on the print-specified loads, the ASD software reveals that the "appropriate" spring is shorter and has fewer coils — which would still meet Crown's print, as the number of coils is an untoleranced reference specification. This "juggling" is expected for manufacturing of parts for which there are allowable tolerances. Within the range of spring geometries that are print-compliant, the geometry-dependent fatigue life will vary.

- The maximum Crown-designed working spring deflection was near the solid height (i.e., full compression) of the spring. Standard practice for the recommended extremes of working deflection range for compression springs are between 15% and 85% of full deflection, and as the spring approaches solid height, the effective spring rate, loads, and stresses rapidly increase[2,3]. See **Figure 8** from Associated Spring's *Engineering Guide to Spring Design*[2].
- Per the print dimensions, at full switch driver stroke, the spring deflection was over 98%. Utilizing the print dimensions and tolerances with the ASD software results in the load vs. length composite image in **Figure 9**, which has been visually augmented and enhanced for clarity. As solid height is approached each time the switch is cycled, adjacent coils will clash due to normal variations in coil pitch — as there is less than 0.002 inches of space between each coil at maximum deflection. Additionally, given the force tolerances on the print and recognizing the allowable variability in the spring geometry, it can be seen that at the upper limit of the force tolerance, the spring approaches permanent plastic deformation at full compression (denoted by the green line labeled "Preset Required"). Preset will be discussed below.
- Note that due to the non-linearity of the spring rate as the spring compression approaches 100% (**Figure 8**), the "loads based on print dimensions" trace in **Figure 9** is unrealistically constant in the "NOT RECOMMENDED" area of the plot.
- As facilitated by the near-solid-height maximum deflection of the spring, cyclical coil clashing will over time eventually cause the anti-corrosion plating to deform and/or wear away from the areas of coil contact, potentially allowing corrosion to introduce stress raisers in these areas. Clashing may also cause localized plastic deformation and other surface flaws that create fatigue crack initiation sites.
- As a backup to the ASD software analysis, manual calculations of the peak torsional stress in the spring were performed as follows, based on Spring Manufacturers Institute formulas[4]:

$$\tau = \frac{8(Fmax)D}{\pi d^3} * K_w \qquad K_w = \frac{4C-1}{4C-4} + \frac{0.615}{C}$$

(Equation 1)

D = spring nominal diameter (to wire centerline)

d = wire diameter

C = D/d

- Common practice is to compare these stresses with the minimum tensile strength of the spring wire — in this case (for ASTM A228 music wire) 353,000 psi[5]. The Crown drawing for the spring, however, specified only music wire (not music wire manufactured to ASTM A228). At the upper load tolerance in full deflection,

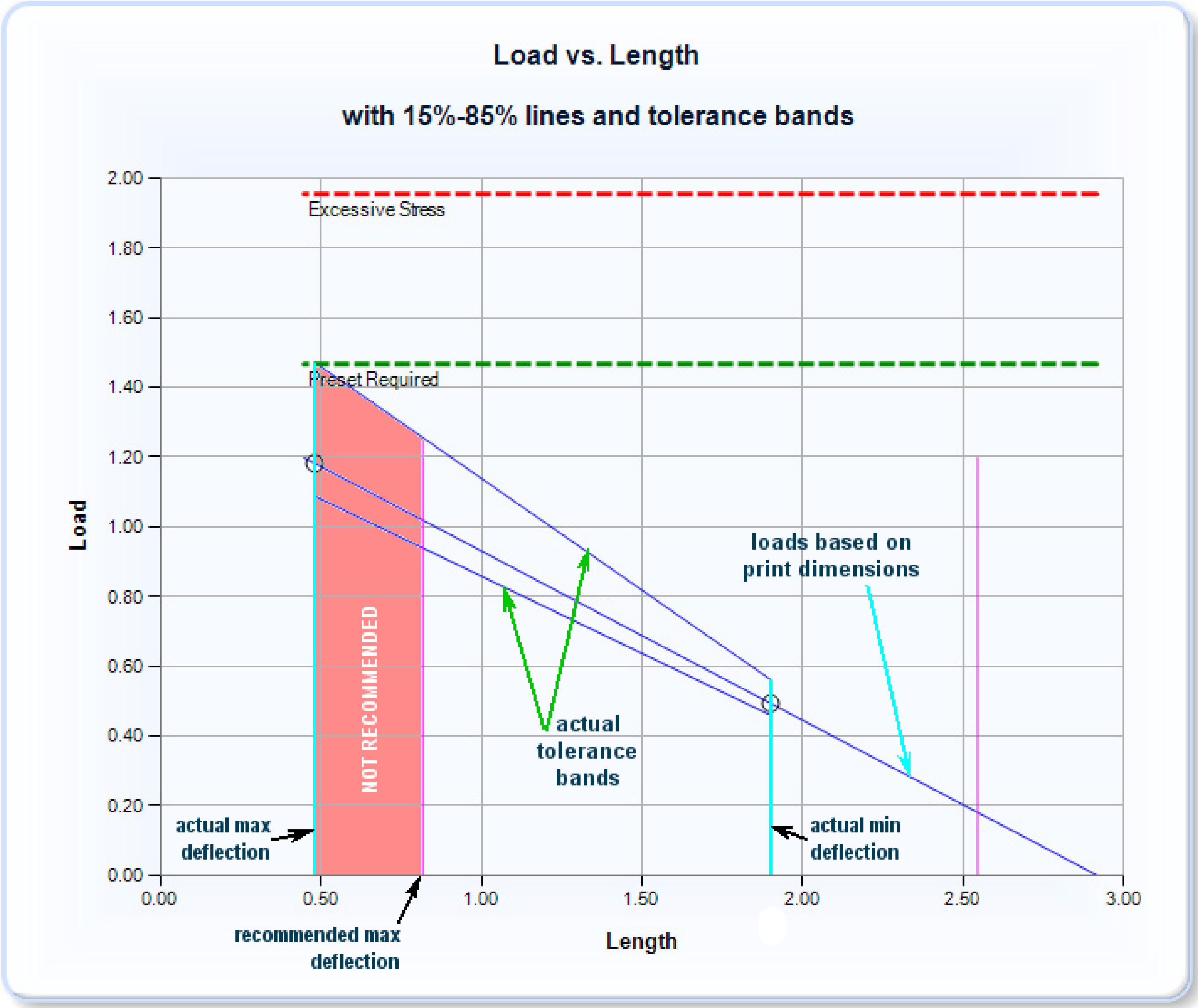

Figure 9
Load vs. length composite image.

torsional stress was 160,000 psi, which when divided by 353,000 = 45.3%. This agreed closely with the spring in **Figure 9** reaching a "preset" (permanent plastic deformation) level of stress, and agrees with Spring Manufacturers Institute documentation of 45% as the threshold of preset[4]. Presetting, in which the spring is intentionally deformed beyond its yield strength, is used in some spring designs to reduce localized stresses, but the subject spring was not designed for preset.

- As to consideration and analysis during design of the previously listed issues of fatigue life variability, over-deflection, buckling, and clashing, no Crown documentation had been provided in discovery that reveals how the design was created. Regarding the ASD estimation of the spring's fatigue life, which again is calculated at nominal dimensional values, the ASD software documentation states *"The estimated fatigue life is applicable to ambient temperature conditions when… springs are preset, material surface is free from seams, burrs, and other stress risers…and the spring does not buckle, have interference, or bind in fixtures"*[3]. In the subject Crown application, the springs were not preset, the spring material quality was not controlled, and the springs had interference. Various references discuss the use of Weibull plots and statistical evaluation of a significant number of tested-to-failure springs, for evaluating fatigue life[6,7]. There is no evidence whether such analyses were performed by Crown during design of the subject spring. The personnel at spring manufacturer Delmar were unfamiliar with these types of analyses.

- Given the marginal spring design, several key elements should have been in place to mitigate the risks of using the design: 1) use top-quality spring wire materials; 2) conduct validation testing to foreseeable conditions; 3) maintain continuous manufacturing oversight through ongoing durability testing and quality assurance; and 4) maintain oversight of field performance through warranty claim monitoring and (as needed) root cause analysis. Elements 1, 3, and 4 will be discussed below, while a discussion of element 2 would require disclosure of confidential information.
  - The Crown drawing specified only that "music wire" be used. There was no print specification that the wire was to be certified to ASTM A228, though Delmar always used ASTM A228 wire from various wire mills. The mills' certificates of compliance for the wire were provided to Crown by Delmar with every order; these certificates included Crown-required basic chemical and physical analyses. No microscopic inspection of wire samples was required by Crown, nor were wire mill certificates required to be provided. Further, there were no Crown controlling documents that set any higher expectations for wire quality, documentation, inspection, or testing beyond what was practiced by Delmar in producing the springs. Additionally, the level of documentation provided by Delmar in its initial Production Part Approval Process (PPAP) submittal was accepted by Crown. If the longitudinal radial cracking originated with wire manufacturer Echo, it would not have been compliant with ASTM A228. But Delmar had no contractual requirement to second-guess the ASTM A228 certification papers (provided by the wire mills) and perform its own verification of compliance.

- After years of spring production beginning in the late 1990s — and about two years before the subject switch was produced — Delmar notified Crown that the supplies of pre-tinned wire available to meet the Crown-specified material requirements had a high scrap rate when used for the subject spring design. Apparently, tin-plated wire was becoming unpopular in the market due to environmental concerns associated with tin, and fewer quality suppliers were offering tin-plated wire. Delmar offered to use a superior-quality zinc-coated wire it had in stock, without a production delay or cost increase to Crown. In production, springs made of this zinc-plated wire had a much lower scrap rate of 5% compared to springs made from the pre-tinned wire, which had a scrap rate as high as 40%. Crown denied the request, and apparently chose not to consult its customer Baker about using the superior wire.
  - Crown was in a unique position among all defendants to understand the safety implications of using other than top-quality wire for this spring design in this high-cycle control switch application, given the marginal spring design. Its decision was not defended by Crown's deponents.

- Crown's engineering witness (a representative speaking for the company, per Federal Rules of Civil Procedure Title V Rule 30[b]6) was asked in his deposition about the continuous conformance testing required for the switch per Alpha's performance specification. The witness believed this consisted of a few thousand cycles of testing that were so brief that they were focused on proper product assembly and not on ensuring continuing compliance with durability requirements. In fact, per Alpha's performance specification, this testing was short-term durability testing to be done on several production samples each day. Continuous conformance testing was a separate requirement in Alpha's specification, consisting of ongoing tests wherein one sample was run several hundred thousand cycles. Upon completion of the test, another test was begun with a new production sample. Several tests could be completed per year, at the testing rate called for in Alpha's spec. Such durability testing would reasonably meet the DFMEA design controls specified for addressing switch component fatigue. But Crown's witness had no evidence that the incident switch's assembly plant performed either the short-term durability testing or the continuous conformance testing required by Alpha.

- With the spring failures that were brought to its attention, Crown failed to reach a competent

conclusion on root cause in every documented case. Indeed, Crown's 30[b]6 witness stated (when deposed 10 years after the initial spring failures) that Crown didn't know the root causes of the failures.
- In his deposition, Crown's quality engineer had exhibits of several different corrective action reports, but was not able to identify any true root cause determinations.
- Baker's quality engineer requested at one point that both Crown and Delmar each conduct independent analysis reports on the spring failures. Delmar hired a test lab, and Crown decided it would simply rely on Delmar's report.

<u>Control system manufacturer "Baker"</u>

- As the manufacturers of the control system that utilized the control switch, and having knowledge of the design of that switch, Baker failed (in the opinion of the author) to appropriately manage safety risks associated with using that switch.
  - Per Baker's 30[b]6 engineering witness, it was not necessary to notify the federal government (re TREAD Act[8] requirements) about the broken control switch springs because the problem description in many switch warranty claims described a failure of the vehicle to start — apparently not a safety concern to Baker. Baker eventually admitted that broken springs could also defeat the safety interlock, presenting a safety issue in vehicles overall.
  - A key source of information regarding the performance and reliability of the switch would be warranty returns. Indeed, warranty returns triggered the initial inquiry into spring issues. Yet Baker apparently did not track all switch warranty claims through to a full understanding of the root cause of the failures.
    - The Alpha warranty database showed that over a two-year period in the mid-2000s there were more than 100 warranty claims with a problem description that the switch was "binding, sticking, or seizing," over 50 warranty claims with a description "grounded" or "short circuited," and over 50 warranty claims with a description that the switch was "making noise." Each of these descriptions was consistent with broken springs, and while many of these warranty claims were likely due to other causes, there does not appear to have been any tangible investigation, cause determination, or corrective action documented for the vast majority of the claims. As the Alpha warranty database provided in discovery only had records for two model years of vehicles, it could not be queried for earlier switch warranty claims that may have preceded what Baker referred to as its first notice of the problem.
  - After Crown finally agreed to accept spring manufacturer Delmar's request to allow the superior quality zinc-plated wire to be used in place of the pre-tinned wire, Crown submitted a change request to Baker a few months later, and Baker rejected this win-win request. Baker had done its own stress analysis of the spring; the reason given for rejecting the spring wire change was that spring redesign was necessary to reduce peak torsional stresses along with a material change — and Baker did not want to simply change the wire material while the redesign was underway. But the net effect of Baker's rejection of Crown's change request was that the superior-quality wire was not used by Delmar until the spring redesign and engineering change was implemented over two years later. There appears to be no rational reason why the change to zinc-plated wire could not have been put in place right away.

- Among nearly all discovery-revealed communications and change notices within and between defendants Alpha, Baker, and Crown, they neglected to highlight that failures of the subject control switches could be dangerous to vehicle owners. The primary conflicts between these parties amounted to discussions of costs and chargebacks.

- Ultimately, there are numerous examples where Baker and Crown personnel recognized the need to redesign the spring. The manner in which these defendants balanced the safety risks inherent in the design involved compromises they did not necessarily need to make, as the subject design was not the only way to create a control switch. The subject spring geometry was obviously not the only geometry that could be chosen. Additionally, at the time the subject vehicle's switch was created, feasible alternative technologies and designs existed with superior durability. Baker had produced all-electronic control switches with no springs in the early 2000s.

Summary of Opinions

- Delmar was not involved in the design decisions or risk evaluations pertaining to the spring or its use in the control switch. Delmar consistently manufactured the springs to Crown's specifications and requirements. Delmar proactively sought to replace the pre-tinned wire with a superior alternative, but this was denied by Crown and Baker. Once the spring was redesigned (slightly shorter overall length, slightly larger diameter wire), the failures generally stopped, despite Delmar using the same manufacturing equipment and processes as before the redesign.

- In designing and manufacturing the subject control switch, Crown failed to properly consider the safety of the end-user, as manifested by its faulty DFMEA, failure to eliminate known spring failure contributors from the design, failure to timely implement the Delmar-recommended change to a higher-quality wire, apparent failure to conduct required production-line durability testing, failure to timely implement the redesign of the spring, and failure to competently evaluate and remedy the root causes of spring failures.

- In utilizing the subject switch in its control system assemblies, Baker failed to properly consider the safety of the end-user, as manifested by its failure to timely implement the Delmar-recommended change to a higher-quality wire, failure to timely implement the redesigned spring, and failure to properly evaluate warranty returns of switches.

- In the case file materials, there were test reports showing laboratory testing of switches to millions of cycles. There were examples provided as well (by other experts in this litigation) of vehicles that had hundreds of thousands of miles on their original switch, yet there was no information about the usage history of these vehicles — for example, if they were used for highway commutes or in urban stop-and-go traffic. Regardless of these issues, the fact that a subset of switches may last a long time is not proof that all switches will do so — and the warranty claims for this switch backed this up. The allowable tolerance variations in the springs would in itself introduce variability in peak stresses with the opportunity for those stresses to be excessive.

- At the time the subject vehicle's control switch was produced, known and feasible alternatives existed that would have reduced or eliminated the hazard that led to the subject fatality.

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