Tech-Spring Report B

Stress Analysis Methods for Springs

An Assessment of Low Cost Spring Stress Analysis Tools

Introduction

This is the first of two reports examining low and high cost analysis tools, their procedures for use and validation of the methods. This report specifically addresses the low cost tools and as such covers deliverables 3.2 (Procedures for Use), 3.3 (Integration into Software) and 3.4 (Validation of Low Cost Tools).

The low cost analysis tools identified as deliverable 3.1 in the first year of the project were as follows:-

1. Load / torque testing of springs.
2. Dimensional measurement of springs.
3. The use of Almen strips.
4. Photo elastic films.
5. Stroboscopic Lights
6. Camera monitoring of springs
7. Strain Gauging of Springs
8. Spring design CAD software.

Each tool is examined in turn to identify its uses, advantages, problems, usage and methods of validation and any other specific issues.

Load / Torque Testing of Springs

The main function of load or torque testing is to confirm that a spring is capable of resisting or supplying a given force at a given length or angular displacement, which is usually already given by the spring designer on a spring design drawing. This technique is largely a confirmatory step in spring manufacture, ensuring that the design requirements have been met. A test can be completed relatively quickly, and with good accuracy by spring makers, with just a modest amount of training. It is common for the use of spring design CAD software and load or torque testing to be combined in the spring manufacturing process to provide confirmation that the spring prestressing (if any) had been accomplished and that the springs are not overstressed.

Virtually all of the technical reports issued under the Tech-Spring program have made use of load or torque testing simply because the test is fast, gives excellent accuracy, and gives a clear indication of the applied load (from which the stress is calculated) of the spring under test.

Spring load or torque test machines themselves may range from under €1000 up to €90,000 depending upon size, load capacity and accuracy, but will typically be used many thousands of times over a year to verify many millions of springs, making the machine cost per test minimal. Relatively simple fixtures are required in addition to the test machine to enable torque tests to be performed – these fixtures are often specific to the spring type and form being tested, but are usually considered as “tooling” for a particular job, and stored for repeat business.

A typical fully automatic spring test machine is shown in figure 1 below.

Figure 1

Figure 2 contains examples of the test results (on four unused sample springs from one of the initial Tech-Spring reports) that the above test machine can generate:-

Institute of Spring Technology
Henry Street
Sheffield
S3 7EQ
ENGLAND
Tel: +44 (0)114 2760771
Fax: +44 (0)114 2726344

	Machine Type:	LT3-2500-3
	Manufactured By:	Institute of Spring Technology Henry Street, Sheffield, S3 7EQ, United Kingdom
	Tel:	+44 (0)114 276 0771
	Software Copyright:	© IST 2001-2008

TEST INFORMATION

Part Number:	4 comp. spring from 810 job		
Job Number:	810		
Customer:	ist		
Batch:	[001]		
Test Date:	13/03/2009 13:54:12	Tested By:	so
Comments:			
Signed:		Date:	

MACRO DETAILS

Part Number:	4 comp. spring from 810 job
Created:	13/03/2009 13:52:11

Command	Value	Times
SET MACHINE TYPE	LT3-2500-3	
SET LOAD UNITS	N	
SET LOAD RANGE	2500	
SET LENGTH UNITS	mm	
SET SPRING TYPE	Compression	
SET AUTOTARE	ON	
SET MAX SPEED	25 (20 mm/sec)	
START	ON	
GOTO FREE LENGTH		
GOTO LENGTH	70	
RECORD (1) LOAD		
GOTO LENGTH	60	
RECORD (2) LOAD		
GOTO LENGTH	50	
RECORD (3) LOAD		
GOTO LENGTH	40	
RECORD (4) LOAD		
GOTO LENGTH	85	

TEST RESULTS

	Recorded Parameter	Units	-Tol	+Tol
1	LOAD	N		
2	LOAD	N		
3	LOAD	N		
4	LOAD	N		

13/03/2009 14:09 Page 1 of 2

4 comp. spring from 810 job : 810 : 001

	Spring Number	1	2	3	4
1	LOAD	49.5	54.5	54.5	54.5
2	LOAD	90.5	95.5	96.0	95.0
3	LOAD	133.5	138.5	137.5	139.0
4	LOAD	179.5	181.5	181.0	183.0

STATISTICS

Data Format: All springs
Springs tested = 4 Springs analysed = 4
Number of groups = 4 Sub group size = 1

		Minimum	Maximum	Average
1	LOAD	49.5	54.5	53.3
2	LOAD	90.5	96.0	94.3
3	LOAD	133.5	139.0	137.1
4	LOAD	179.5	183.0	181.3

		Range	No. Low	No. High
1	LOAD	5.0	N/A	N/A
2	LOAD	5.5	N/A	N/A
3	LOAD	5.5	N/A	N/A
4	LOAD	3.5	N/A	N/A

		Std. Dev.	Cp.	Cpk.
1	LOAD	2.5	N/A	N/A
2	LOAD	2.5	N/A	N/A
3	LOAD	2.5	N/A	N/A
4	LOAD	1.4	N/A	N/A

13/03/2009 14:09 Page 2 of 2

Figure 2

The load tests (figure 2) and the dimensional tests (figure 3) have been used to generate the spring design CAD results (figures 9-12) for the same springs to illustrate the accuracy of the software prediction, and the interactive nature of design / load test / dimensional test in confirming the applied stress of a design. A spring can be designed, samples made and tests performed to confirm (or otherwise) that the samples meet the design – if not then the design is modified and further samples made and tested until a working design is achieved.

Dimensional Measurement of Springs

Dimensional inspection of springs is largely a confirmatory step in spring manufacture, but is widely used during manufacture to check that the original spring design has been met, because it is a quick and reliable method of monitoring and controlling the manufacturing process.

The complexity and variety of spring features that are possible means that potentially a whole range of measurement equipment is required to enable all features to be measured. More typically dimensions are checked on a sample basis by the spring maker during manufacture. Experience operators will tend to measure the most critical or meaningful dimensions rather than all of the possible dimensions. There is always a danger that a design drawing tolerances absolutely every dimension on a spring, when only a modest number of features actually need to be measured to ensure that the spring is fit for purpose. Over tolerancing just adds to manufacturing cost and manufacturing difficulty whilst generating little benefit to the end spring user.

The combination of spring design CAD software with load or torque testing and dimensional inspection provides a high degree of confidence to the spring maker that the finished spring is correct and not overstressed.

The following figure shows an example of a dimensional report for the springs load tested in figure 2, and designed by spring design CAD software in figures 9 – 12.

Spring number	Wire Diameter(mm)	Number of Coils	Outside Diameter (mm)	Free Length (mm)
1	3.2	5.1	43.30	82.90
2	3.2	5.1	43.32	82.58
3	3.2	5.1	43.40	82.74
4	3.2	5.1	43.38	82.69

Figure 3

The Use of Almen Strips

Almen strips are a cheap means (€1 each to buy) of process monitoring the effect of shot peening (it is possible to add Almen strips into every batch of springs that are shot peened as a result, despite the single use nature of the strips). Almen strips do not directly measure the residual stress within a spring, but give an indication that a suitable residual stress should have been developed. An Almen strip is clamped onto a test block, and put into the peening cabinet with a batch of springs during peening. After peening the Almen strip is removed from the Almen test block and it will assume an arc shape along its long axis (One side of the strip is peened , whilst the other side is protected by the test block – this difference in compressive stress causes the test strip to assume an arc shape when unclamped). There is a need for substantial peening process validation steps to ensure that the so called "arc rise" from an Almen strip is an adequate guide. There is a substantial amount of technical data and pre existing application information in various text books that details the process monitoring requirements necessary to ensure consistent results.

Use of Almen strips as an indirect means of quantifying residual stress during the shot peening process (whether carried out in-house by springmakers, or subcontracted) is a low cost process monitoring technique. Direct measurement of residual stress is an expensive process and will be discussed in the 'high cost spring stress analysis tools'.

The following figures give examples of an Almen gauge, Almen gauge blocks and "arc rise" on an Almen strip after peening:-

Figure 4

Figure 5

Figure 6

Photo Elastic Films

This is an experimental non contact optical stress analysis technique that relies upon coating an item to be measured with a special stress sensitive coating. The coating can display an effect called temporary birefringence (double refractive index). Under an applied stress the coating splits light into two components travelling at different speeds. When the light emerges from the object the beams are out of phase, with the difference in phase being related to the applied stress by the following equation:-

$$(\sigma 1 - \sigma 2) = \frac{N}{t} \frac{E}{(1+v)} \frac{\lambda}{K}$$

Where:-

E = the modulus of elasticity
N = the Poissons Ratio
K = a strain constant for the material
t = the coating thickness
1 = the wavelength of light used

This technique could be used by the spring industry in reflective modes. The object to be measured is then viewed through a polariser using special light sources, so that a number of interference fringes can be viewed on the object. The number of fringes can be related to the strain and therefore the stress applied to the object. By loading a spring in a test machine a calibration between the number of patterns observed and a stress level can be made. Originally very time consuming and tedious manual techniques were used to calculate the stresses in an object that required highly skilled operators. Now digital imaging and computer based systems are generally used to speed up the process.

This technique is complementary to strain gauging and / or finite element analysis, but is a significantly low cost method of evaluating applied stress. Temperature limits of this technique are 0 – 60° C and it can handle dynamic stresses, if the speed of loading is relatively slow. This technique would only be used for complex strip spring components where the position of maximum applied stress is not readily apparent.

Stroboscopic Lights

This low cost technique involves using a precisely controlled and rapidly flashing light to illuminate a spring periodically during motion. Viewing the spring whilst the strobe is flashing will serve to freeze the spring's motion when the strobe frequency matches the spring's actuation frequency. This is largely used to observe springs operating at high speeds to ensure that no resonance effects were occurring at a resonant frequency or a harmonic of that frequency. There must be direct line of sight to the spring and sufficient space to allow the stroboscope and observer access. There is however some potential risk to the observer if a spring should unexpectedly break. The method will simply identify when there are additional dynamic stresses but will not quantify them.

Camera Monitoring of Springs

Cameras can be used to monitor the movement of springs during fatigue testing to provide a means of identifying when a spring breaks. This allows remote monitoring of a spring during test, and allows unattended testing to be performed provided that the camera can be located in direct line of sight of the spring. Cameras may be combined with stroboscopic lights to "freeze" a spring's motion for later analysis.

The camera is potentially vulnerable to damage should a spring break, but modern webcams suitable for this application can be obtained for under €50.

Strain Gauging of Springs

Strain gauging has been considered as a low cost tool in this report – this will be true if the spring maker has the in house expertise and equipment in order to be able to install and monitor strain gauge outputs. Strain gauges can be purchased individually for considerably less than €50 each, and the total equipment required costs less than €500. Only the strain gauge itself is consumed. Some smaller SME spring makers have neither adequate expertise or specialist equipment, let alone the time that it takes to produce a working strain gauge installation. In this case the spring makers becomes dependent upon outside resource and this technique moves towards being a high cost analysis technique.

Strain gauging is a contact analysis technique where a direct strain measuring element is mounted onto the surface of an item to be measured. These are usually photo etched metallic foil shapes mounted on a flexible backing media. The strain gauge is then connected to a separate signal conditioning and display unit by cabling. The need for cable connections between items of equipment is a potential restriction to the use of this technique.

Careful selection of the strain gauge alloy material, flexible backing material, adhesive system, strain gauge resistance, temperature compensation coefficient and gauge length of the strain gauge are necessary to obtain the accuracy and reliability of strain measurement for a given material and spring size. It is physically possible to attach strain gauges to springs down to 3mm wire diameter, and the accuracy achieved during the project was shown to be sufficient. If the directions of the principle stresses within a spring are not known then it will be necessary to resolve this uncertainty by using rosettes of strain gauges mounted onto a single backing film in which three individual gauges are oriented at known angles to each other (usually 45°, 60° or 90°). Multiple channel equipment will be required to analyse these rosettes – this is clearly a higher cost tool.

High stability, low noise signal conditioning equipment is necessary to measure the very small resistance changes in strain gauges during operation. Often the quality of the installation of a strain gauge onto a spring will be critical to the accuracy and durability of the gauges operational life.

When a spring is loaded or fatigue tested the investigator is actually interested in the applied stress present in the spring – this is a feature that cannot be measured directly by this technique. The conversion of measured strain into a derived stress is accomplished by reference to the Young's Modulus (E) of a material.

The procedure for use of strain gauging is as follows:-

1. Select the spring and the feature to be measured.
2. Select the correct strain gauge configuration and construction for the expected measurement to be made. Fatigue applications will require larger and heavier strain gauge installations than for static tests – the Manufacturers guidance literature need to be examined carefully.
3. Prepare the surface of the spring to accept a strain gauge (de-greasing).
4. Install the strain gauge using special epoxy based cement or super glue.
5. Allow the cement to dry completely before use of the gauge, otherwise the installation may fail prematurely. Strain gauges are often not successful due to failure of the bonding to the item of interest, rather than a failure of the gauge itself.
6. Cover the gauge in protective resin to preserve the working life of the gauge.
7. Install connecting wires to the strain gauge power supply system, switch the system on and allow the gauging system to stabilise. Additional dummy gauges may be needed to provide temperature compensation within the gauge assembly.
8. The spring needs to be operated, and the corresponding strain read off of the monitoring equipment.
9. Perform calculations to ensure that the strain gauge is giving a strain output that is proportional to the deflection applied. This should then be compared with stress values calculated via conventional mechanical theory to ensure that sensible results have been obtained.
10. Appropriate data logging is required to ensure that the required data is recorded.

The main advantage of this technique is that it is possible to determine the surface stress in a spring as the result of application of a load upon the spring. The main disadvantage is that a strain gauge cannot measure any residual stress that has been introduced into a spring prior to installation of the gauge – this technique is completely incapable of identifying pre existing residual stress patterns generated as a result of shot peening for example.

The main disadvantage of strain gauging springs is that they operate in 2-d only and most springs are three dimensional. Strain gauge rosettes are necessary for measuring the direction of maximum applied stress and sticking these to the doubly curved inside surface of a compression spring creates difficulties for the technician charged with sticking the gauge in place.

Strain gauge measurements need to be carefully validated by use of accurate values of Youngs Modulus (E), and by applying known loads to a spring so that accurate values of strain can be measured and hence stress can be calculated.

The following figure shows a typical strain gauge installation on a spring:-

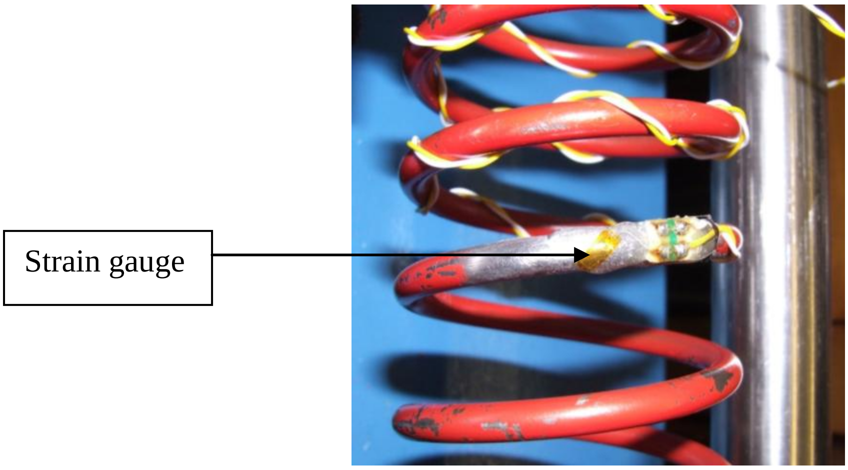

Figure 7

Spring Design CAD Software

Spring Design CAD software is based upon classical mechanics theory for springs, and uses formulae in spring design standards such as EN 13906 parts 1,2 and 3, SAE, JIS and BS. This project confirmed that the applied stresses calculated by these methods are accurate and repeatable with two important exceptions. CAD programs use the formulae in the standards, so stresses are calculated accurately. CAD programs also have performance data built into them so that springmakers can predict the performance that their customers can expect. The project has identified a number of deficiencies / ommissions in the data in typical CAD programs, but has confirmed that the data is always conservative, and hence safe. Some partners argued that the data was often overly conservative, but correcting this fault was too big a task to be dealt with, and this was not an objective of this project.

This predictive method of assessing spring perfomance is very strongly recommended as being quicker and cheaper than other predictive method and is nearly as accurate as any other method investigated during this project. This method should be used whenever possible by the spring maker. The spring design CAD software can be used in two main ways:-

1. Checking customers designs to ensure that a design is possible and practical.

2. Spring makers creating an original spring design from basic requirements supplied by the customer.

It is recommended that some form of design check is made on all springs before manufacture commences to ensure that designs are practical and reliable.

Incorporation of extensive material files and actual performance data within the software by the software writers significantly increases the confidence of the CAD user in the spring designs created.

Spring design CAD software does not deal with any residual stresses present within the springs, and can only handle springs that are axially symmetric and made from wire or strip.

The following figure details the stages in performing a spring design using CAD software:-

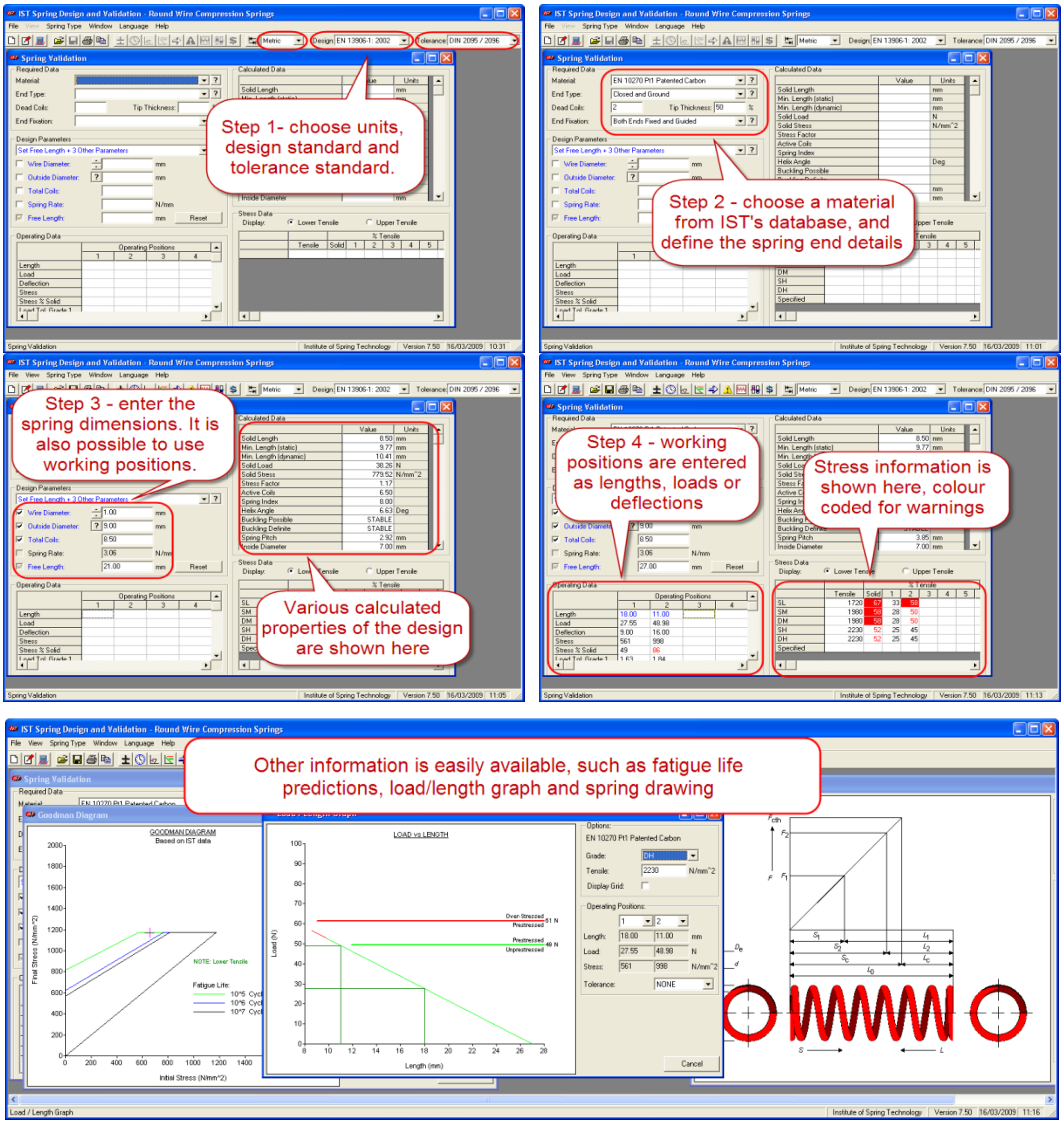

Figure 8

The following figures are screen prints from the spring design CAD toolkit, and show a typical design page (Figure 9), a spring drawing (figure 10), a Goodman diagram (figure 11), and a load length diagram (figure 12) as examples of the types of outputs that can be obtained.

INSTITUTE OF SPRING TECHNOLOGY Date: 16/03/2009 08:51:16

Spring Type Round Wire Compression

Designed To:	EN 13906-1: 2002		
Tolerance Standard:	DIN 2095 / 2096		

Material

BS 2056 Austenitic Stainless

Youngs Mod (E):	187500	N/mm^2	
Rigidity Mod (G):	70300	N/mm^2	
Density:	.00000797	Kg/mm^3	
Unprestress:	0-45	%	
Prestress:	45-56	%	
End Type:	Closed and Ground		
Dead Coils:	1.70		
Tip Thickness:	50.00	%	
End Fixation:	Both Ends Fixed and Guided		

Design Parameters

Wire Diameter:	3.20	mm	
Outside Diameter:	43.32	mm	
Total Coils:	5.10		
Spring Rate:	4.20	N/mm	(Calculated)
Free Length:	83.02	mm	

Calculated Data

Solid Length:	16.32	mm
Min. Length (static):	19.97	mm
Min. Length (dynamic):	21.80	mm
Solid Load:	279.90	N
Solid Stress:	872.67	N/mm^2
Stress Factor:	1.11	
Active Coils:	3.40	
Spring Index:	12.54	
Helix Angle:	10.26	Deg
Buckling Possible:	STABLE	
Buckling Definite:	STABLE	
Spring Pitch:	22.82	mm
Inside Diameter:	36.92	mm
Mean Coil Dia.:	40.12	mm
Wire Length:	649.84	mm
Weight / 100:	4.17	Kg
Natural Freq:	11726	RPM

Stress Data

	Lower Tensile	Solid	% Tensile / Operating Positions 1	2	3	4
301S26 G1	1250	70 O	14 U	24 U	35 U	45 U
301S26 G2	1500	58 O	11 U	20 U	29 U	38 U
302S26 G1	1230	71 O	14 U	24 U	35 U	46 P
302S26 G2	1470	59 O	12 U	20 U	29 U	38 U
Specified						

Operating Data

	Operating Positions 1	2	3	4
Length (mm)	70.00	60.00	50.00	40.00
Load (N)	54.62	96.59	138.55	180.52
Deflection (mm)	13.02	23.02	33.02	43.02
Stress (N/mm^2)	170	301	432	563
Stress % Solid	20	35	50	64
Load Tol. Grade 1 (N)	8.78	9.18	9.57	9.97
Load Tol. Grade 2 (N)	13.94	14.57	15.20	15.82
Load Tol. Grade 3 (N)	22.30	23.30	24.31	25.32
O.D. Expansion (mm)	0.224	0.396	0.568	0.740

Figure 9

INSTITUTE OF SPRING TECHNOLOGY Date: 16/03/2009 08:59:09

Spring Drawing		Right hand helix	
	Material:	BS 2056 Austenitic Stainless	
d	Wire Diameter:	3.20	mm
D_e	Outside Diameter:	43.32	mm
n_t	Total Coils:	5.10	
R_s	Spring Rate:	4.20	N/mm
L_0	Free Length:	83.02	mm
L_c	Solid Length	16.32	mm
F_{cth}	Solid Load	279.90	N
	Operating Positions		
L_2	Length:	60.00	mm
F_2	Load:	96.59	N
L_1	Length:	70.00	mm
F_1	Load:	54.62	N

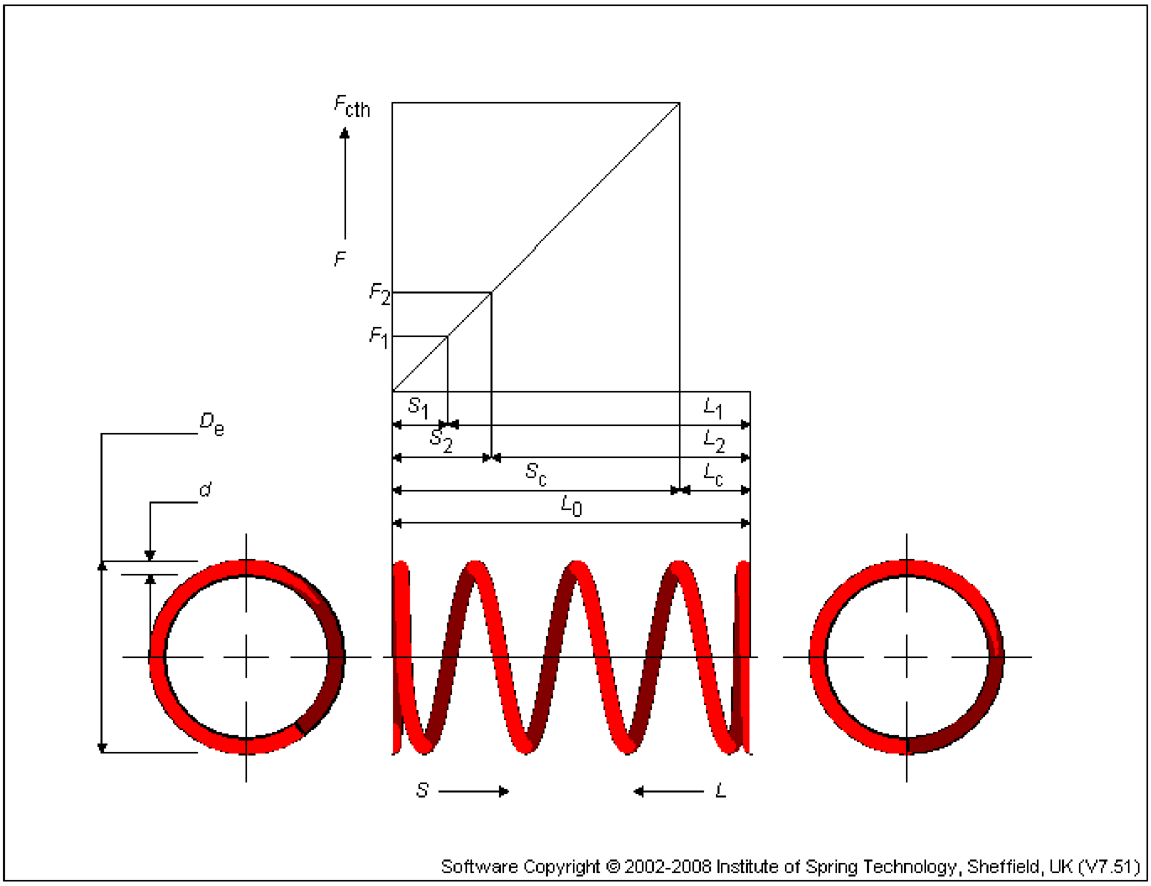

Figure 10

INSTITUTE OF SPRING TECHNOLOGY Date: 16/03/2009 09:00:17

Goodman Diagram

Material:	BS 2056 Austenitic Stainless
Grade:	302S26 G1
Shot Peened:	No
Pre-Stressed:	No

Operating Positions

	1	2
Length (mm):	70.00	60.00
Load (N):	54.62	96.59
Corrected Stress (N/mm^2):	188	333

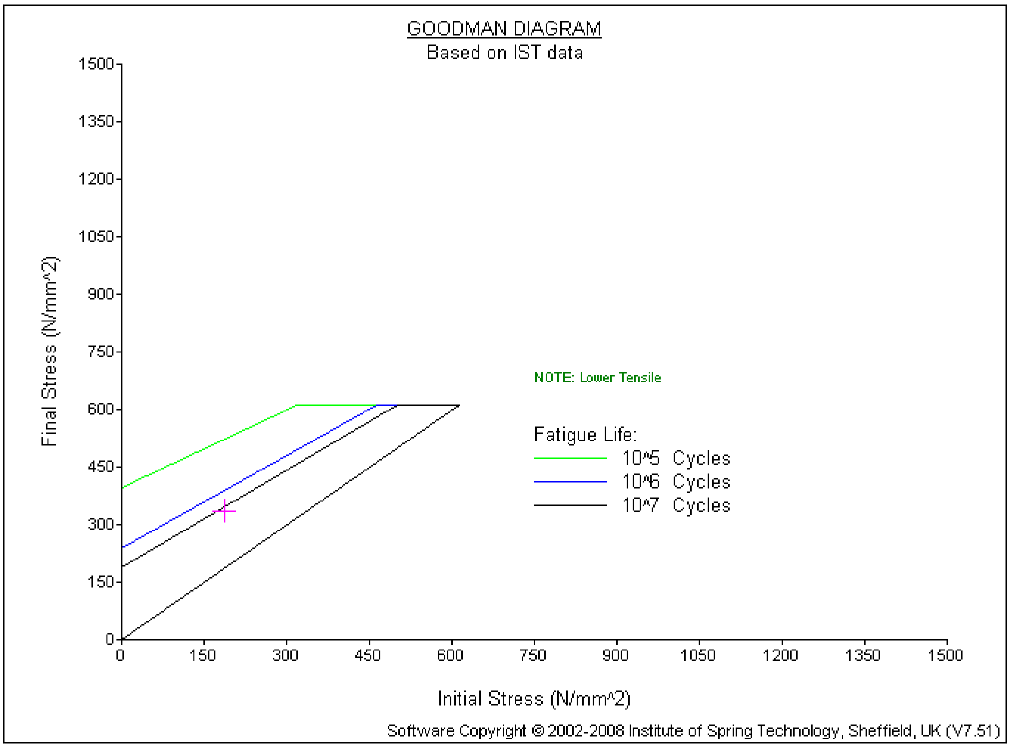

Figure 11

INSTITUTE OF SPRING TECHNOLOGY Date: 16/03/2009 09:01:12

Load / Length Graph

Material:	BS 2056 Austenitic Stainless
Grade:	302S26 G1
Lower Tensile (N/mm^2):	1230

Operating Positions

	1	2
Length (mm):	70.00	60.00
Load (N):	54.62	96.59
Stress (N/mm^2):	170.29	301.14

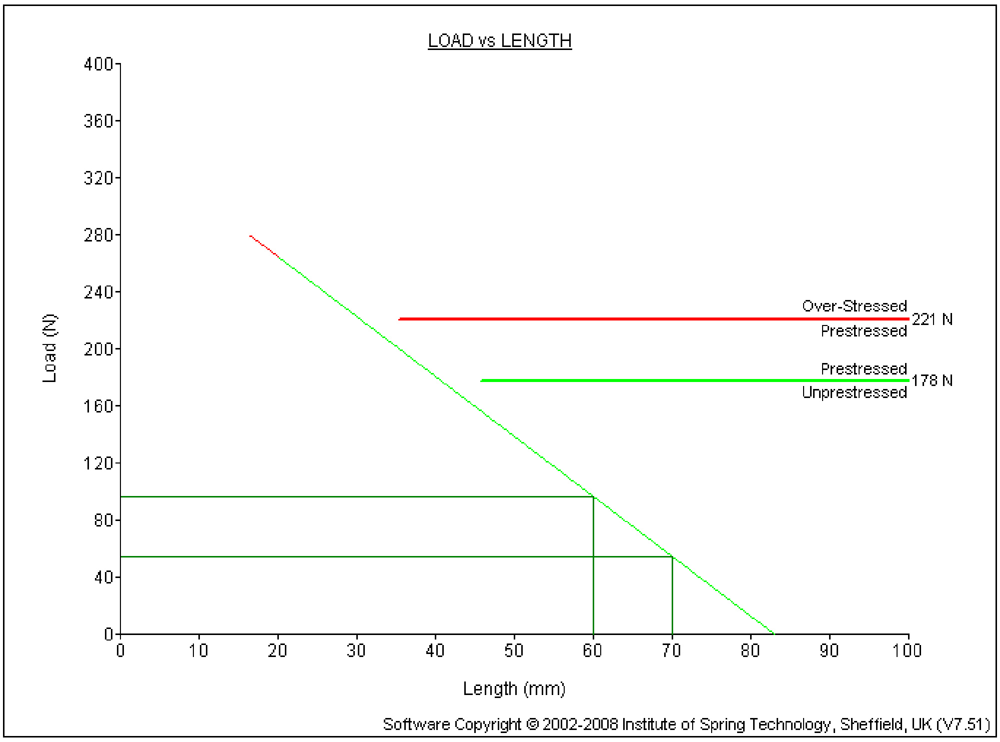

Figure 12

Conventional Mechanics Formulea

All the formulae used in EN13906-1 and 2 were shown to be accurate. In addition, the formulae used in the Tech-Spring Toolkit for the calculation of bending stress in the end hooks of extension springs was shown to be accurate. However, the formulae for calculating the rate of extension springs ignores the possibility of elastic/plastic deflection of the hook. A warning has been inserted into the toolkit when the number of active coils is few (i.e. <20). With a large number of active coils the rate calculation is sufficiently accurate.

The calculation formulae for stress in torsion springs (EN13906-3) is not correct. It advises that uncorrected should be used for static applications and corrected stresses for dynamic applications. The correction is for the curvature of the wire and is completely unnecessary. A correction is necessary for the tilting and shearing of the active coils. Derivation of this correction factor was attempted within the project, but insufficient data was available. This task was beyond the scope of the project and so will have to be considered in a future project. At least Tech-Spring has shown the reason for, and way, that the correction may be effected, and that a classical mechanics solution is possible.

Conclusions

This report has identified and examined all of the low cost spring analysis tools, identifying methods of use and applicability of each technique. All of the identified techniques are low enough in cost, and of a relatively modest technical nature to enable SME spring makers to potentially deploy these tools themselves from their own internal resources. It is not unusual to see the majority of these techniques in use at spring makers around the world (the possible exceptions being photo elastic films, and strain gauges which require a higher level of technical capability to employ.

The three techniques that have become far and away the most popular with spring makers are spring design spring design CAD software, load testing and dimensional inspection, which when used in conjunction with each other give the spring maker a high confidence in the accuracy of the stresses in the springs they produce. The conventional mechanical formulae used for calculation stresses in springs have been shown to be accurate except in the case of extension springs with few coils, and torsion springs.

Author: Andrew Watkinson, IST