

ALLOWABLE STRESSES FOR HELICAL COMPRESSION AND TENSION SPRINGS OF ROUND WIRE

1. NOTATION

c	spring index = D/d		
D	mean diameter of spring	m	in
d	wire diameter	m	in
f	bending stress (in tension spring hook)	N/m ²	lbf/in ²
N	endurance		
q	shear stress at inner surface of coils due to applied load as computed by Equation (4.1) of Data Item No. 82008*	N/m ²	lbf/in ²
q_r, q_s	shear stress in outer fibres of wire during prestressing process (see Sketch 3.1)	N/m ²	lbf/in ²
R	stress ratio = q_{min}/q_{max}		

Suffixes

lim	indicates limiting value of static stress
min, max	indicate minimum and maximum values of stress respectively, as computed by Equation (4.1) of Data Item No. 82008

Both SI and British units are quoted but any coherent system of units may be used.

* Data Item No. 82008, "Elastic stresses and deflections of helical compression and tension springs of round wire".

2. NOTES

This Item provides data on both the fatigue and static strengths of various spring materials. The data presented relate to prestressed springs, heat treated after manufacture in cases where this has a beneficial effect on the fatigue life (see Section 6.4) and operating in a non-corrosive, normal temperature environment. For most carbon steel spring materials, a normal temperature falls in the range -20°C to $+150^{\circ}\text{C}$. Further data on allowable operating temperatures for other materials are given in Data Item No. 83003*.

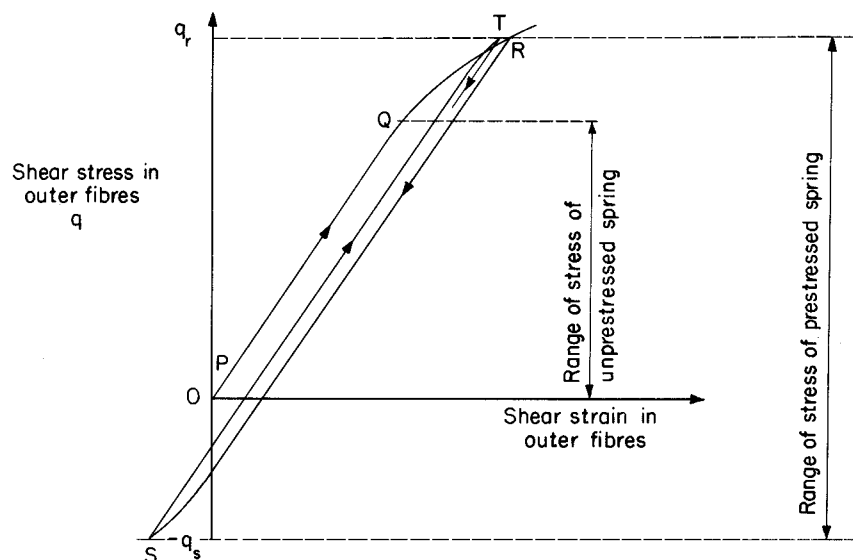
In general, both the static and fatigue strengths should be checked in any design. Static criteria alone may be used for springs subjected to only a few hundred cycles in their working life.

An index to the materials dealt with and the data sources for the allowable stresses may be found in Table 9.1.

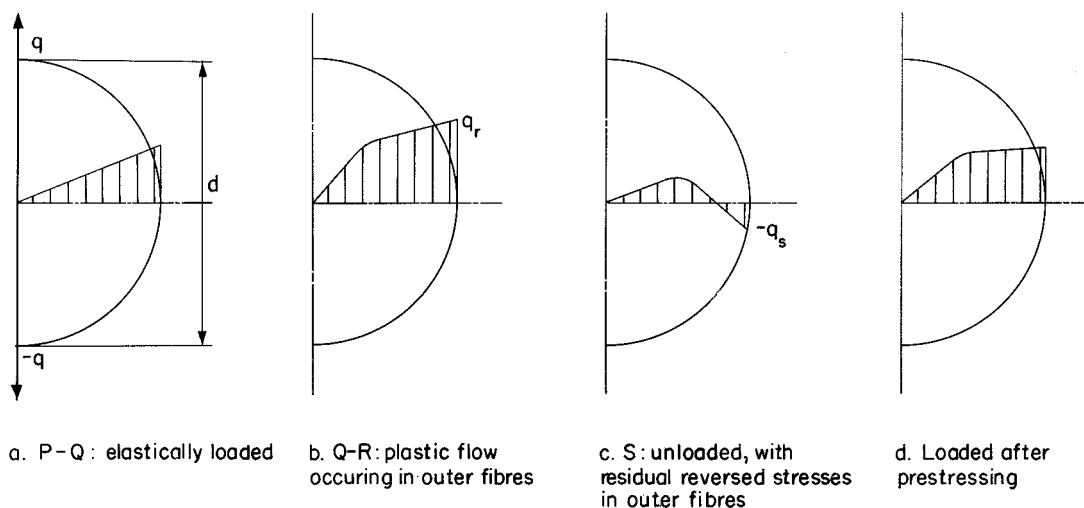
* Data Item No. 83003, "Notes on the design of helical compression and tension springs of round wire".

3. PRESENTATION OF STATIC DATA

3.1 Compression Springs



Sketch 3.1 Shear stress in outer fibres of spring wire during prestressing



Sketch 3.2 Stress distribution before, during and after prestressing, super-imposed on wire diameter

The shear stress, q , in this Item refers to springs that have been manufactured so as to contain a beneficial prestress. Prestressing enables springs to be loaded in service beyond the point that would ordinarily produce plastic deformation, and therefore permanent set. Sketches 3.1 and 3.2 show the stress distribution during the prestressing process. The spring is initially wound long and is then stressed elastically under a compressive load from P to Q (Sketch 3.1) and then plastically to closure from Q to R. Releasing the load leads to the reversed residual stress, $-q_s$. Subsequently, the spring can accept a change of stress, $|q_s| + |q_r|$ while remaining elastic. This is the stress calculated using Data Item No. 82008. In practice, the spring is compressed to solid 5 or 6 times (S to T *et cetera*) to complete the process. Figures 1 to 5 present typical values of q_{lim} obtained from measurements on prestressed springs, as a function of wire diameter. Once

the major spring parameters have been determined, the stress when the spring is compressed to solid may be calculated. This stress should not exceed the values given in Figures 1 to 5.

Usually, one of the first steps in the spring design process is to choose a value of stress corresponding to the maximum working load. For a spring sustaining only static loads, this should be as high as reasonably possible, normally about 85 per cent of the values given in Figures 1 to 5. This criterion should maintain adequate clearance between the coils when the spring is compressed to its minimum working length (see Section 6.3 of Data Item No. 83003).

3.2 Tension Springs

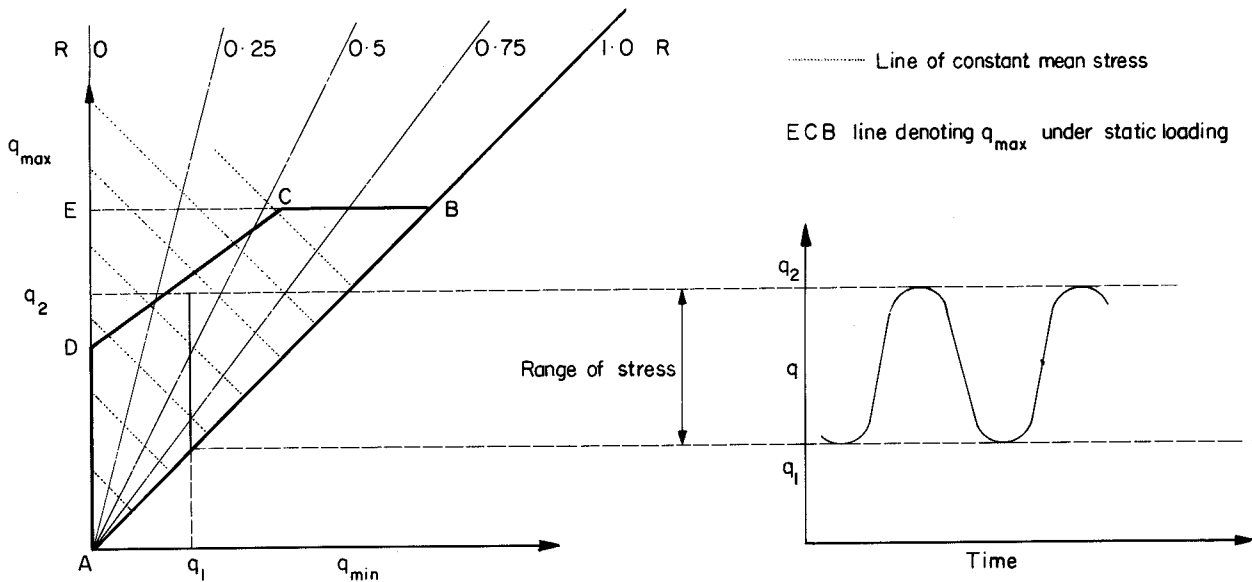
The coils of a tension spring are usually held together when unloaded by an initial tension, requiring a load to be applied before the spring begins to extend. In effect, an initial tension provides an in-built elastic pre-stress, but this should not be confused with the “prestressing” process applied to compression springs, which consists of plastically deforming the spring. The additional load required to open the coils of such a tension spring must be included when calculating the stress.

The limiting static shear stress diagrams (Figures 1 to 5) may be applied to the working coils of tension springs, provided the maximum calculated stress is reduced by about 20 per cent to account for the lack of prestressing, a process which is not applied to such springs. This stress should not exceed the torsional yield stress of the material. The most important stress in a tension spring, however, is usually the bending stress present in the end hook. Figures 6 to 9 relate the maximum allowable bending stress in a tension spring as a function of wire diameter for various materials. In the absence of any yield data, the maximum stress in Figure 6 is based on 50 per cent of the tensile strength; that of Figures 7, 8 and 9 is based on fatigue testing of torsion springs to 10^4 cycles, the wire in such springs being stressed in bending.

4. PRESENTATION OF FATIGUE DATA

4.1 Compression Springs

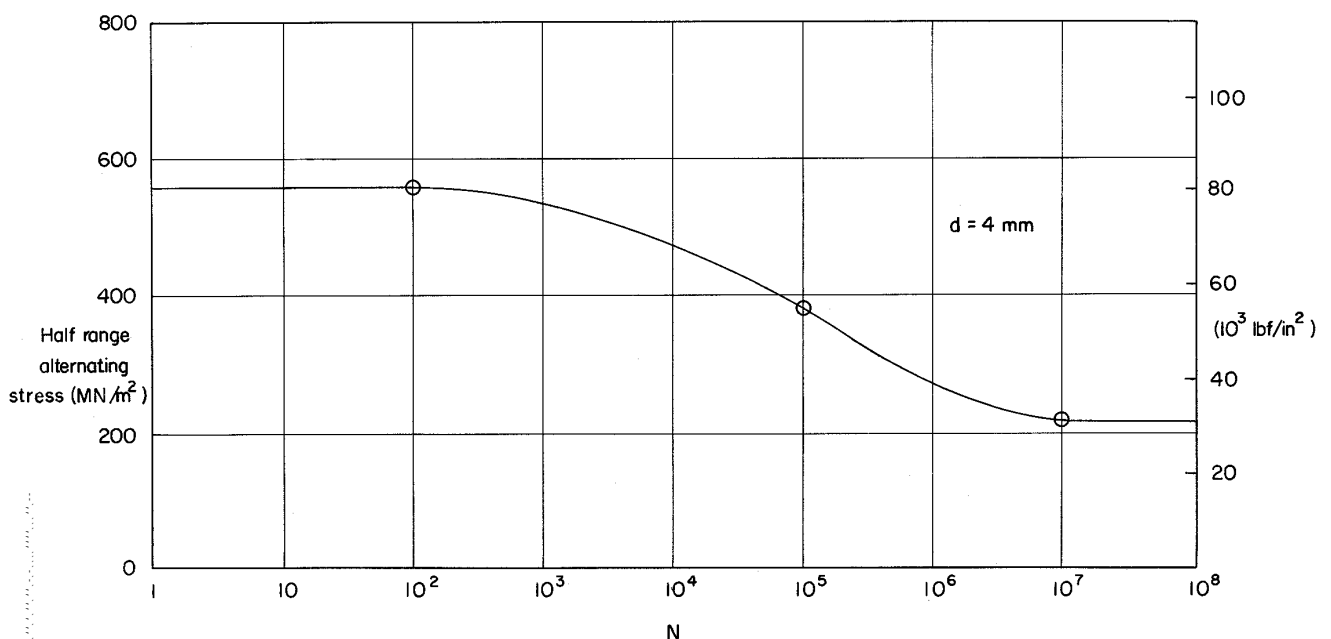
ABCD denotes area of allowable range of operating stress for specific endurance



Sketch 4.1a Example modified Goodman type diagram for specified values of N and d

Sketch 4.1b Stress-time diagram for spring cyclically loaded between q_1 and q_2

Sketch 4.1 Presentation of fatigue data



Sketch 4.2 Estimated S-N curve for BS 1408 Range 3 at constant mean stress: 500 MN/m^2

Fatigue data are presented on modified Goodman type diagrams, Figures 10 to 22, for various materials and wire diameters. These figures relate to prestressed springs where the minimum and maximum stresses in the spring, q_{min} and q_{max} , are calculated from the loads and geometry using Data Item No. 82008. The figures provide data for fatigue lives of 10^7 cycles and, where data is available, 10^5 cycles. The data for 10^7 cycles may be taken as the fatigue limit for ferrous materials. Sketch 4.1a shows how these stresses are presented on a modified Goodman type diagram, and their relationship to the stress cycle of the spring is shown in Sketch 4.1b. The example in Section 8 illustrates the use of the figures. Figures 23 and 24 refer to straight wire which does not, therefore, have the benefit of prestressing. The data are presented as $S-N$ curves for a fixed stress range $R = 0.1$. Mean curves are drawn through the data.

4.1.1 Estimation of an $S-N$ curve

Where two values of stress (at endurance of 10^5 and 10^7 cycles) are available from the fatigue diagrams, they may be combined with the static stress value to estimate a complete $S-N$ curve. The curve may be drawn for either a specified value of mean stress or R as required. Sketch 4.2 shows an $S-N$ curve for carbon steel, unpeened springs to BS 1408 Range 3, for a constant mean stress of 500 MN/m^2 . A line representing this mean stress has been drawn on Figure 10 and the values for Sketch 4.2 have been taken from the intersection of the line and the appropriate endurance curves. The “static” value (taken from Figure 1) has been extended to 10^2 cycles (as suggested in Section 2) and, since this is a ferrous material, 10^7 cycles has been taken as the fatigue limit. These zero gradients enable a curve to be estimated between 10^2 and 10^7 cycles.

Note that BS 1408 has now been superseded by BS 5216: 1975, for which few data are at present available. However, while BS 5216 is nominally only a metric revision of BS 1408 it also includes improved surface finish requirements. Any errors in using this data will thus be conservative. BS 5216; Grades 1, 2 and 3 replace BS 1408; Ranges 1, 2 and 3 and BS 5216; Grades 4 and 5 replace BS 1408M; Ranges 1 and 2.

4.2 Tension Springs

Where tension springs are subjected to fatigue conditions, it is wise to ensure that the most significant stress occurs in the working coils and not in the hook end design, since unknown residual stresses may occur therein. Data Item No. 83003 provides information on suitable end connection designs. The data contained in the Goodman diagrams may be used provided the maximum stress is reduced by about twenty per cent to account for the lack of prestressing in tension springs. No bending fatigue data are included in this Item.

5. FACTORS AFFECTING SPRING LIFE

5.1 Spring Geometry

At small values of the spring index, c , the shear stress at the inner surface of the coils is noticeably increased owing to the curvature of the wire. This effect is accounted for by the curvature correction factor used in Data Item No. 82008 when calculating q . Springs coiled from small diameter wire can withstand higher operating stresses than larger sizes for two reasons. A greater reduction in wire diameter by drawing during manufacture improves the mechanical properties and secondly, the springs may be coiled from cold wire. If hot coiled springs are subsequently heat treated, then decarburisation problems may result.

The greater static strength of smaller wire diameters is clearly illustrated in Figures 1 to 9. A similar improvement is also gained in fatigue strength, as shown by some of the fatigue diagrams. Further information on geometrical effects may be found in Derivation 15.

5.2 Corrosion

The fatigue life of springs operating in a corrosive atmosphere may be drastically reduced; possibly to as little as 10 per cent of their fatigue life in air as given by this Item. Springs may be protected by plating but this may wear away where the wires touch at the end of the active coils. Corrosion resistant materials such as titanium, stainless steel or copper-nickel alloys are better. Further guidance on corrosion is given in Data Item No. 83003.

5.3 Surface Finish

Flaws, machine marks, *et cetera*, marring a wire surface may lead to earlier failure, cracks initiating more easily at a poor surface. A good surface finish may be obtained by specifying valve spring quality wire.

5.4 Elevated Temperatures

High operating temperatures tend to induce a permanent set or loss of load in springs at a fixed deflection and a reduction in the shear modulus. Temperatures as low as 120°C may cause relaxation of, for instance, music wire (BS 1408M, ASTM A228 *et cetera*) although other materials can withstand higher temperatures (see Section 4.3 of Data Item No. 83003).

6. TREATMENTS IMPROVING FATIGUE LIFE

6.1 Prestressing

Prestressing is a process applied to compression springs to improve the static and fatigue properties. It is described in detail in Section 3.1 of this Item and Section 3 of Data Item No. 83003.

6.2 Shot Peening

Shot peening is carried out by blasting small pellets at the spring. It has the most beneficial effect where the torsional stress is greatest at the inside of the coils, which makes shot peening impractical with closed tension springs and difficult to accomplish with springs of small diameter wire. After peening, the springs should be given a low temperature heat treatment to enhance further fatigue life. Peening leaves a very active surface which should be protected to stop corrosion. The process improves fatigue life in three ways.

- (a) Introduces residual compressive stresses which reduce the overall tensile working stress at the surface.
- (b) Hardens the surface. Part of the improvement in fatigue life due to shot peening may be attributed to increasing the hardness of the surface. Note that shot peening has less effect on harder wires.
- (c) Improves the surface finish. Shot peening can remove small surface imperfections but the process should not be relied upon to improve very poor or decarburised surfaces. The small indentations left by the shot have no deleterious effects on crack propagation.

Further information on the effect of shot peening may be found in Derivation 7. Indication is given on the figures if the data refer to shot peened springs.

6.3 Abrasive Cleaning

Abrasive cleaning improves the fatigue life by smoothing the surface of the spring, although it has the disadvantage of removing material from the wire. It is accomplished by blasting abrasive particles at the spring using compressed air or water. The surface should be immediately protected against corrosion. The effect of abrasive cleaning is shown on Figures 23 and 24.

6.4 Low Temperature Heat Treatment

This process is used to alleviate residual stresses induced by coiling the spring and is only usually applied to ferrous materials, one exception, however, being Inconel. It is also used to improve fatigue life after shot peening.

7. DERIVATION AND REFERENCES

7.1 Derivation

This section lists selected sources that have assisted in the preparation of this Item.

1. ZIMMERLI, F.P. Relation of Wahl correction factor to fatigue tests of helical springs. *Trans Am. Soc. Mech. Engrs*, Vol. 60, pp. 43-44, January 1938.
2. MEYERS, O.G. Working for helical springs. *Machine Design*, pp. 135-138, November 1951.
3. BURNETT, H.C.
STAUGAITIS, C.L. Endurance of helical springs related to properties of wire. *Metal Progress*, pp. 79-81, September 1953.
4. BURNETT, H.C. Torsional fatigue properties of small diameter high carbon steel wire. *Proc. ASTM*, Vol. 58, pp. 515-527, 1958.
5. CSFRO Coil Spring Federation Research Org., Sheffield, Report No. 112, LSG/P5, April 1959.
6. TEMPERED SPRING Co. Ltd Unpublished work by the Tempered Spring Co. on Titanium alloy springs, June 1962.
7. HAYNES, R. The influence of residual stress due to shot peening on the fatigue behaviour of silicon manganese spring steel. *Strain*, Vol. 3, No. 4, October 1967.
8. FUNKE, P.
KAYSOR, K. Statische und dynamische untersuchungen an federn aus sieben verschiedenen Federdrahten nach Din 17224. *Draht*, Vol.22, No. 5, pp. 315-328, 1971.
9. BSI Specification for patented cold drawn carbon steel wire for mechanical springs. British Standards Institution, BS 5216: 1975.
10. GRAY, S.D. High performance spring materials for aircraft. S and T Memo. 5-75 (DRIC-BR-47967), April 1976.

11. HAYMAN, E.L.
GREENWOOD, D.W.
MARTIN, B.G. The torsional fatigue properties of titanium alloy spring wire. *Exp. Mech.*, Vol. 17, No. 5, p. 161, May 1977.
12. SRAMA Spring Research and Manufacturing Association, Spring design data sheet No. 7, September 1977.
13. CARLSON, H. Spring fatigue – recommended design stresses. *Am. Soc. Mech. Engrs* paper No. 78-DE-5, May 1978.
14. BSI Specification for pre-hardened and tempered carbon and low alloy round steel wire for springs for general engineering purposes. British Standards Institution, BS 2803: 1980.
15. KLOOS, K.H.
KAISER, B. Fatigue properties of helical springs as functions of spring index and surface condition. Part 1, *Wire*, Vol. 31, No. 2, pp. 65-70, March-April 1981. Part 2, *Wire*, Vol. 31, No. 3, pp. 130-136, May-June 1981.

7.2 References

The references given are recommended sources of information supplementary to this Item.

16. BERRY, W.R. *Spring design*, Emmott, London, 1961.
17. WAHL, A.M. *Mechanical Springs*, Second Edition, McGraw-Hill, 1963.

8. EXAMPLE

It is required to choose a suitable material for the compression spring designed in the example in Section 13.1 of Data Item No. 82008. The major characteristics are (from Sections 13.1.3, 13.1.6 and 13.1.9 of that Item);

$$d = 2.5 \text{ mm}, c = 11, q_{max} = 526 \text{ MN/m}^2, q_{min} = 48.9 \text{ MN/m}^2,$$

the stress when compressed solid = 560 MN/m^2 , and,
the maximum static stress = 425 MN/m^2 .

The spring is to operate in a non-corrosive environment and have infinite life.

8.1 Static Loading

In the example, a deliberately low value of static stress was chosen to allow for the expected higher stresses induced by cyclic loading. Referring to Figures 1 to 5, with $d = 2.5 \text{ mm}$, all the spring materials shown could easily withstand the stress of 560 MN/m^2 when compressed to solid length.

8.2 Fatigue Loading

As an example, a line has been drawn in Figure 10 showing the range of operating stress of the spring. This starts on the thick 45° line with $q_{min} = 48.9 \text{ MN/m}^2$ and extends vertically to an ordinate value of $q_{max} = 526 \text{ MN/m}^2$. This line falls within the safe stress area for BS 1408, Range 3, unpeened springs for infinite life. Following the same process on Figures 10 to 15, the following list may be compiled of suitable

materials for non-corrosive environments.

BS 1408 Range 1	shot peened
BS 1408 Range 3	unpeened
BS 2803: 094A65	unpeened
ASTM A228 music wire	unpeened
BS 2803: 730A65	shot peened
BS 2803: 685A55	shot peened

9. TABLES

TABLE 9.1 Table of Materials

Material type	Material classification	Location (Figure Number)			
		Static torsion	Static bending	Fatigue	Derivation Number
Carbon steel	BS 1408	1		10	12
	(BS 5216)		6		9
	BS 2803: 094A65	1		11	12
			6		14
	ASTM A227, A228	2	7		13
	A229, A679			12	1, 2, 3, 4, 13
Chrome-vanadium alloy steel	BS 2803: 730A65	3		13	12
	ASTM A231	3	8	13	13
	Chrome-silicon alloy steel	3		14	12
	ASTM A401	3	8		13
Stainless steel	BS 2056	4		15	12
	DTD 5086	4		16	12
	FV 520(S)			17	10
	BS S205			18	10
	ASTM A313	4		17	13
	DIN 17224			19, 20	8
Titanium alloy	4 Al-4Mn (Ti 314A)*			21	5, 6
	13V-11Cr-3Al			23	11
	3Al-8V-6Cr-4Mo-4Zr			24	11
Beryllium-copper	ASTM B197	5	9	22	13
	Phosphor-bronze	5	9	22	13

* UK Specification

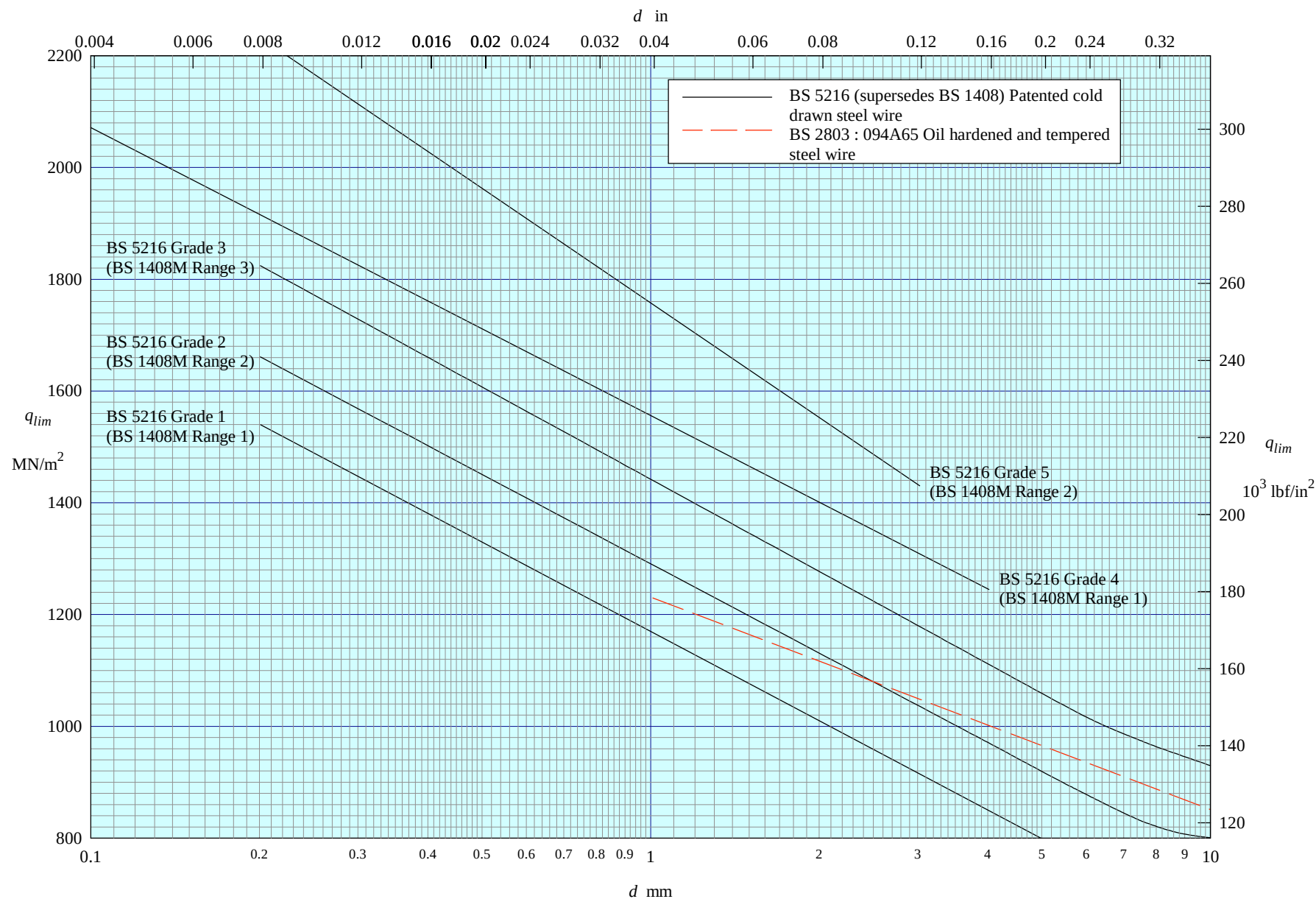


FIGURE 1 LIMITING STATIC SHEAR STRESS FOR CARBON STEEL SPRINGS TO BS 1408 AND BS 2803

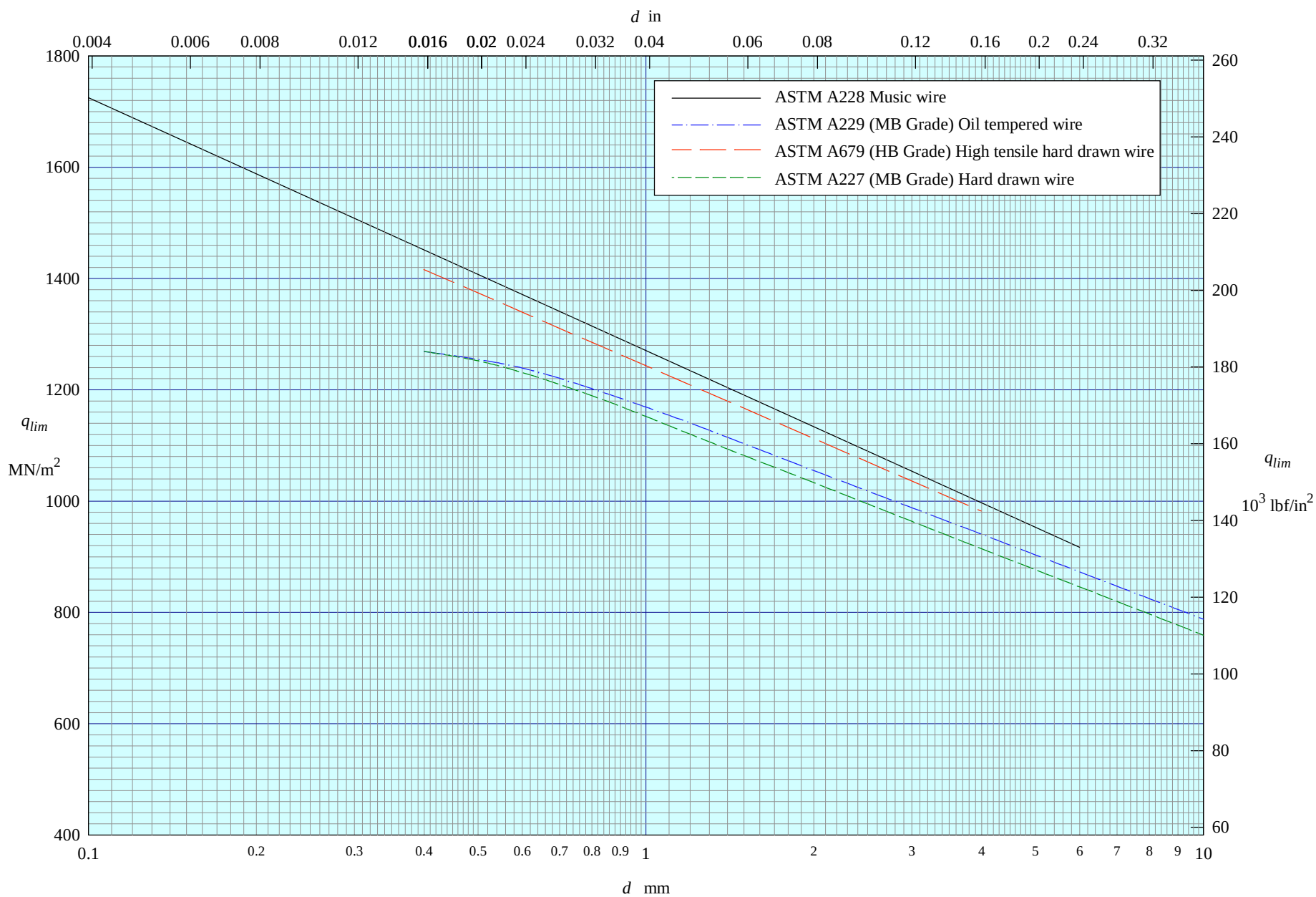


FIGURE 2 LIMITING STATIC SHEAR STRESS FOR ASTM CARBON STEEL SPRINGS