Use of Characteristic Curves in the Design of Elastomeric Pavement Seals

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This paper describes and illustrates a relatively simple technique for predicting performance of and designing certain elastomeric seal sections. The approach relies on characteristic curves. The emphasis is on practical applications. The basic advantage of the approach is that the highway engineer can deal with a problem of nonlinear structural analysis without performing the analysis. The procedures suggested do not require anything more than a slide rule or a pocket computer.

Elastomeric seals, because of their high flexibility, seem to be well suited for sealing expansion joints in highway pavements. This paper illustrates how the results of some earlier research (1, 2, 3) on elastomeric seals may be used by the highway engineer for practical predictions and design.

The suitability of an elastomeric seal is assessed from a set of standard laboratory tests. An important test in this set is the load-deflection experiment. The purpose of the experiment is to determine whether the product exerts the required forces at the specified minimum and maximum compressions. The characteristic curves and the approach discussed in this paper make it possible to arrive at these values without conducting an experiment. In addition, the characteristic curves may be used in the design of seals that will meet the specified requirements.

The discussion in this paper is restricted to seal sections whose geometry consists of identical, symmetric, V-shaped web members with vertical sidewalls (Figure 1). The section may also have a central vertical diaphragm passing through the apex of each V-shaped segment. The stress-strain curve of the material is assumed to be reasonably linear. It has been shown (1, 2, 3) that with these assumptions one can easily construct an analytical load-deflection curve for a given sample that conforms with the assumed geometry. The analytical technique has yielded results that compare satisfactorily with experimental results.

The theoretical problem is that of nonlinear structural analysis because of the large deformations involved (as much as 40 or 50 percent compression). The highway engineer, however, can bypass this process of nonlinear analysis and use instead the characteristic curves and the expressions given in this paper.

Let us consider a single web member (Figure 2). When the member is loaded by a pair of forces P, it will undergo a compression, say Δ. Next, if we assume that the angle α at the sidewall does not change, a pair of moments M_0 must be exerted by the sidewalls on the member. The relationship among P, Δ, and M_0 depends on the angle α, the modulus of elasticity E, the thickness t of the web member, and the undeformed width 2b from sidewall to sidewall. A study of the relationship of P and Δ will require an independent analysis for each given seal, which in a nonlinear problem would be rather time-consuming. However, we can simplify our task by reducing the specific problem to a characteristic problem by introducing dimensionless force quantities and deflections defined as follows:

$$u^2 = P\ell^2/EI \quad (1)$$

$$v = M_0\ell/EI \quad (2)$$

$$\delta = \Delta/2b \quad (3)$$

Equations 1, 2, and 3 stand for dimensionless force, dimensionless end moment, and dimensionless compression. If we know the values of the dimensionless force u^2 and the dimensionless end moment v for any given compression δ, the corresponding values of P and M_0 can be easily computed from equations 1 and 2. For a given compression δ, the dimensionless force quantities u^2 and v depend only on the characteristic angle α. Then we can cover a wide spectrum of load-deflection responses by constructing curves of u^2 to δ and v to δ for properly selected values of α. These curves are referred to as characteristic curves. The characteristic curves for α varying from 5 to 60 deg in steps of 5 deg are given in Figures 3 and 4. The analytical details have already been given (1, 2, 3) and are therefore not repeated here.

In addition to the characteristic curves, we will need,

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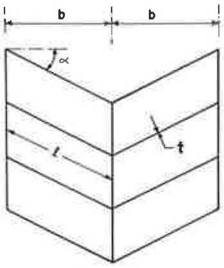

Figure 1. Characteristic section geometry.

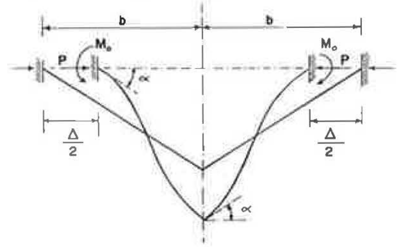

Figure 2. Single V-shaped web member.

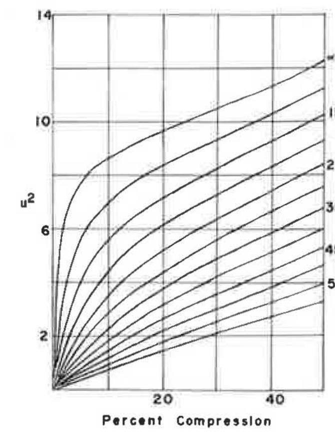

Figure 3. Characteristic curves for the dimensionless force u^2.

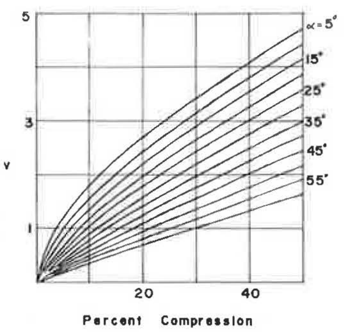

Figure 4. Characteristic curves for the dimensionless moment v.

Table 1. Values of u^2 and v for checking the product performance at 20 and 50 percent compression.

α (deg)	u^2 20% Compression	u^2 50% Compression	v, 50% Compression
5	9.6	12.2	4.70
10	8.4	11.2	4.40
15	7.15	10.2	4.12
20	6.1	9.3	3.82
25	5.2	8.4	3.56
30	4.4	7.55	3.27
35	3.72	6.75	2.98
40	3.18	5.95	2.68
45	2.62	5.25	2.40
50	2.2	4.60	2.13
55	1.8	3.9	1.88
60	1.42	3.3	1.60

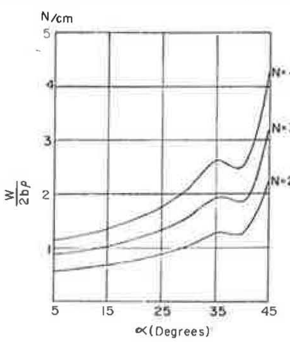

Figure 5. Structural weight versus the characteristic angle *a*.

Table 2. Summary of data for seal design.

	N = 2				N = 3				N = 4			
α (deg)	t_1 (mm)	t_2 (mm)	t_3 (mm)	W/2bρ (N/cm)	t_1 (mm)	t_2 (mm)	t_3 (mm)	W/2bρ (N/cm)	t_1 (mm)	t_2 (mm)	t_3 (mm)	W/2bρ (N/cm)
5	2.46	4.14	4.02	0.569	2.16	3.60	4.02	0.883	1.96	3.28	4.02	1.12
10	2.59	4.29	4.32	0.608	2.26	3.76	4.32	0.912	2.06	3.40	4.32	1.22
15	2.77	4.49	4.10	0.667	2.44	3.91	4.70	1.01	2.21	3.56	4.70	1.34
20	3.00	4.72	5.00	0.765	2.60	4.12	5.20	1.15	2.36	3.73	5.20	1.53
25	3.22	5.00	5.79	0.873	2.32	4.37	5.79	1.32	2.57	3.96	5.79	1.76
30	3.50	5.33	6.57	1.05	3.08	4.67	6.57	1.57	2.79	4.29	6.57	2.10
35	3.86	5.74	7.62	1.28	3.38	5.03	7.62	1.92	3.07	4.57	7.62	2.61
40	4.29	6.27	6.90	1.24	3.71	5.49	6.90	1.87	3.38	4.98	6.90	2.49
45	4.77	6.91	10.90	2.23	4.19	6.02	10.90	3.20	3.78	5.49	10.90	4.26

for performance prediction and design, the expressions given below.

$$P = Cu^2 \tag{4}$$

where C is a constant given by

$$C = [NE_T\beta^2t^3/3\ell^2(1+\beta)^2] \tag{5}$$

and

$$\beta = \sqrt{\frac{E_c}{E_T}} \tag{6}$$

where

P = total force per unit length of the seal,
E_c = modulus of elasticity in compression,
E_T = modulus of elasticity in tension,
t = thickness of the web member,
ℓ = inclined length (Figure 1), and
N = number of identical web members.

The above expressions are of practical value in (a) predicting the performance of a sample that conforms with the assumed geometry and (b) designing a section that will meet a set of specified load requirements. Another important item that should be verified is the value of the maximum compressive stress σ at maximum compression:

$$\sigma = Av + Bu^2 \tag{7}$$

where the constants A and B are given by

$$A = [t\beta^2 E_T/\ell(1+\beta)] \qquad B = [t^2\beta^2 E_T \cos\alpha/3\ell^2(1+\beta)^2] \tag{8}$$

APPLICATIONS IN PERFORMANCE PREDICTION

Some useful applications of the material discussed above will be discussed here with the help of illustrative examples. Let us consider a seal section 1.75 cm wide consisting of four identical web members (N = 4), each 1.78 mm thick with characteristic angle α of 10 deg. Furthermore, for the properties of material of the seal we will assume E_T = 559 N/cm^2, E_c = 363 N/cm^2. [These values are equivalent to those used in illustrative examples in earlier publications (1, 2, 3).] Then from equation 6 we evaluate β = 0.81. For α = 10 deg and width = 1.75 cm we find that ℓ = 0.89 cm. Further, by using the above numerical values in equations 5 and 8, we find that A = 40.7 N/cm^2, B = 1.47 N/cm^2, and C = 1.08 N/cm.

With these data we can quickly generate the load-deflection curve for the seal. All we need to do is use the characteristic curve for α = 10 deg in Figure 3 and the multiplier C = 1.08 already evaluated. We need to read off the values of u^2 for different values of percentage compression and scale these values of u^2 by the multiplier C. The resulting numbers will be the values of force in kilograms per centimeter of seal.

The characteristic curves can also be usefully applied to quickly verify whether a given seal will meet certain specifications. For example, a typical requirement is that the seal at least exert a force P_1 per unit length at 20 percent compression and a force P_2 per unit length at 50 percent compression. The Utah State Department of Highways recommends these values to be 3.51 N/cm and 21.1 N/cm for a 1.75-cm-wide seal. For this check we can use the characteristic curves of Figure 3 or the summarized values given in Table 1. The seal we have been considering here will exert a force P_1 = 8.4C = 8.9 N/cm at 20 percent compression and P_2 = 11.2C = 12.1 N/cm at 50 percent compression. It will therefore meet the specified requirement at 20 percent compression but not at 50 percent compression. The theoretical predictions have been found to be fairly close to experimental results. Hence, a check like the one suggested here can save a substantial amount of experimental work.

Another quantity of interest is the maximum compressive stress at 50 percent compression. This stress can be evaluated by the photoelastic experiments suggested by Cook (4) or by using equations 7 and 8 and the 50 percent compression values given in Table 1. For example, if we use the latter approach, for the seal under consideration,

$$\sigma = Av + Bu^2 = 40.7 \times 4.4 + 1.47 \times 11.2 = 195.5 \text{ N/cm}^2 \tag{9}$$

APPLICATIONS IN DESIGN

So far we have considered the application of characteristic curves in predicting the product performance. These curves can also be used in designing a seal section that will meet specific requirements. To illustrate the process let us consider the following three requirements. The total force P should be P_1 at 20 percent compression and P_2 at 50 percent compression. Further, the maximum compressive stress at 50 percent compression should not exceed an allowable value σ_a. Next we designate t_1, t_2, and t_3 as the thicknesses that correspond with the above three requirements. Then, from equations 4 through 8 we obtain

$$t_1 = [3P_1 b^2(1+\beta)^2/NE_T\beta^2 u_1^2 \cos^2\alpha]^{1/3} \tag{10}$$

$$t_2 = [3P_2 b^2(1+\beta)^2/NE_T\beta^2 u_2^2 \cos^2\alpha]^{1/3} \tag{11}$$

$$t_3 = [3b(1+\beta)/2u_2^2 \cos^2\alpha]\left[\sqrt{v_2^2 + 4/3\,(\sigma_a/E_T)(u_2^2/\beta^2)\cos\alpha} - v_2\right] \tag{12}$$

where

b = half width of the seal (Figure 1),
u_1^2 = value of u^2 at 20 percent compression (Table 1),
u_2^2 = value of u^2 at 50 percent compression (Table 1), and
v_2 = value of v at 50 percent compression (Table 1).

The values t_1 and t_2 depend, as would be expected, on the mechanical properties of the material, the geometry of the seal section, and the number N of identical web members. The value of t_3 depends on the allowable stress σ_a but does not depend on N. For any given configuration, the correct design value of t is the largest of the three values t_1, t_2, and t_3.

Let us consider the design of the seal 1.75 cm wide, i.e., 2b = 1.75 cm. We shall assume the material properties E, β, and so on and the values of P_1 and P_2 to be the same as those in the previous example. In addition, let σ_a = 242 N/cm^2, the value of the allowable compressive stress. Then the only two parameters left are α and N. We can choose a specific configuration angle α and evaluate t_1, t_2, and t_3 from equations 10, 11, and 12 for a practical range of values of N (say, from 2 to 4) and in each case choose the largest value of t as the design value. Then we repeat the entire process for another configuration angle α. By repeating this procedure several times we obtain a set of design values. The values given in Table 2 were obtained by following this procedure. The computations involved are quite simple and straightforward and can be performed with the aid of a slide rule or a pocket computer.

In Table 2, in addition to the thickness, an extra column is added to each category to record numbers that are proportional to the total weight of the web members for the correct design choice. The total weight of the web members per unit length is given by W = $(2b\rho Nt)/\cos\alpha$, where ρ is the weight of the material per unit volume. The results of the weight analysis are shown in Figure 5. It is clear from Table 2 as well as Figure 5 that, in the present case, the lightest satisfactory design corresponds to the lower values of α and the lowest practical value of N. In this case the lowest practical value of N is 2. We also observe from Table 2 that, for α = 5 deg and N = 2, the value of the thickness is governed by the value P_2. In all other cases the design value of t is dictated by the allowable stress. It must, however, be borne in mind that these remarks are valid for the current example. The design values are very much dependent on material properties. Hence, for a different material the indications of Table 2 may be altered.

CONCLUSION

It has been demonstrated in this paper that characteristic curves may be used effectively in making laboratory predictions as well as in designing section geometry. The paper has been confined, for convenience, to the simplest geometry with a high degree of symmetry. However, the procedures described can be extended to more complicated combinations where the web members are not identical in thickness. In such cases, the characteristic curves of Figures 3 and 4 can be used without change provided the seal section does not have a central vertical diaphragm. In such cases the expressions given in equations 4 and 5 should be replaced by the appropriate expression from the report by Vyas (2). In the design procedure illustrated here one can include additional constraints such as the maximum allowable tensile stress and the maximum allowable shear stress. It will require extension of Table 2, but the basic procedure will remain the same. The important advantage of the approach suggested here is the relative ease with which one can handle a problem of nonlinear structural analysis without performing the analysis.

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