DEFORMATION AND EXCESS LOSS IN JACKETED OPTICAL FIBERS UNDER LATERAL PRESSURE

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ABSTRACT

The present work introduces a complete analysis for the deformation and the corresponding excess loss in a double-coated optical fiber due to a lateral pressure. The analysis is based on the theory of elasticity. It is found that the outside pressure has more influence on the deformation in fibers with smaller buffer thicknesses. Design considerations are suggested to minimize fiber deformation and, consequently, the excess loss due to the lateral pressure.

1. INTRODUCTION

Optical fibers with low loss and wide bandwidth have been developed, and there have been vigorous practical uses of transmission systems using these optical fibers. Long-term stability is an important requirement for an optical transmission system, as optical fiber cable is used in a variety of environmental conditions. Therefore, optical fiber cable must maintain stable performance in the most severe conditions.

Optical fibers put in cables may add transmission loss, attributed to microbending of the fiber axis [1-3]. Microbending can result from increases of lateral pressure inside the cable, which imprints irregularities there onto the path of the fiber [4]. The imprinting is accentuated when the materials are stiffer. Dual coating, Figure (1), was introduced to reduce the effect of lateral pressure by buffering the fiber with a soft inner primary layer; the outer secondary layer is hard and robust to allow handling.

In this work the effects of both layers; buffer and jacket, on the fiber deformation are studied. Based on the calculated curvature of the fiber axis, the excess loss due to a lateral pressure is estimated. Section 2 deals with the analysis of the fiber deformation and the excess loss. Results and discussion are presented in Section 3, followed by suggested design considerations in Section 4.

2. MODEL AND ANALYSIS

The fiber under consideration is of the type that has a buffer layer between the fiber and the jacket; Figure (1). The model can apply to both a fiber wound on a drum and a fiber stranded on a tension member inside a cable.

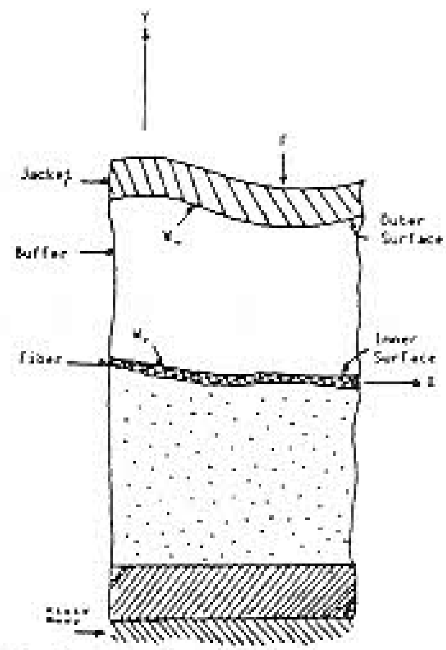

Figure 1. Jacketed optical fiber under lateral pressure.

Outer Diameter Deformation of Jacketed Fibers

Using a Fourier series expansion, the lateral pressure F applied per unit length on the jacket can be expressed by [5]:

$$F = \sum^{n} F_n \left(1 + \frac{n\pi y}{l}\right) e^{-\frac{n\pi}{l} y} \sin \frac{n\pi}{l} x, \qquad (1)$$

where l is the fiber length. The application of this pressure causes a deformation δ in the outer diameter of the jacket given by [6]:

$$\delta = (\frac{\pi}{4} - \frac{2}{\pi})(1 - v_2^2)\frac{FR_2^3}{E_2 I_2}, \quad (2)$$

where v_2 and E_2 are, respectively, Poisson's ratio and Young's modulus of the jacket material, I_2 $(=t_2^3/12)$ is the geometrical moment of inertia for the jacket of thickness t_2, and R_2 is the average radius of the jacket $\{(D_1+D_2)/4\}$ with D_1 and D_2, respectively, the outer diameters of the buffer and the jacket.

Neglecting the change in the jacket thickness with respect to the buffer deformation, the deformation W_o in the buffer outer diameter can be approximated to:

$$W_o = \delta. \quad (3)$$

For simplicity, we call:

$$A = \frac{\pi}{4} - \frac{2}{\pi} \quad (4)$$

The use of equation (1) in equations (2) and (3) yields:

$$W_0 = A(1 - v_2^2)\frac{R_2^3}{E_2 I_2}\sum^{n} F_n(1 + \frac{n\pi y}{l})e^{-\frac{n\pi}{l}y}\sin\frac{n\pi}{l}x$$

$$= \sum^{n} (W_{out})_n(1 + \alpha_n y)e^{-\alpha_n y}\sin\alpha_n x, \quad (5)$$

where

$$(W_{out})_n = A(1 - v_2^2)\frac{R_2^3 F_n}{E_2 I_2}, \quad (6)$$

and

$$\alpha_n = \frac{n\pi}{l}, \quad (7)$$

The nth term in equation (5) is:

$$(W_o)_n = (W_{out})_n(1 + \alpha_n y)e^{-\alpha_n y}\sin\alpha_n y. \quad (8)$$

Buffer Effect

To simplify the problem, a two dimensional model, Figure (1), is used. The equilibrium equation for the buffer can be obtained as a solution of the Airy stress function [7]:

$$\frac{\partial^4\varphi}{\partial x^4} + 2\frac{\partial^4\varphi}{\partial x^2\partial y^2} + \frac{\partial^4\varphi}{\partial y^4} = 0. \quad (9)$$

The solution can be expressed as:

$$\varphi = h(y)\sin\alpha_n x, \quad (10)$$

with

$$h(y) = C_1\cosh\alpha_n y + C_2\sinh\alpha_n y + C_3 y\cosh\alpha_n y + C_4 y\sinh\alpha_n y. \quad (11)$$

where C_1 to C_4 are constants to be determined. Using equations (10) and (11), one can get the stresses σ_x, σ_y and τ_{xy}, through the stress function φ, from the definitions:

$$\sigma_x = \partial^2\varphi/\partial y^2, \quad (12)$$

$$\sigma_y = \partial^2\varphi/\partial x^2, \quad (13)$$

and

$$\tau_{xy} = -\partial^2\varphi/\partial x\partial y. \quad (14)$$

From the definition of Young's modulus of elasticity, the buffer deformation W in the Y-axis can be obtained as:

$$W = \int\frac{\sigma_y}{E_1}dy, \quad (15)$$

where E_1 is the Young's modulus of the buffer material. The constants C_1 to C_4 are determined from the boundary conditions of the buffer which are:

i- At the buffer inner surface (y = 0):

$$\sigma_y = 0 \quad \text{and} \quad \tau_{xy} = 0. \quad (16)$$

ii- At the buffer outer surface (y = t):

$$(W_o)_n = (W_{out})_n(1+\alpha_n t)e^{-\alpha_n t}\sin\alpha_n t \quad \text{and} \quad \tau_{xy} = 0. \quad (17)$$

Using the definitions represented by equations (12-15) and solving equations (16) and (17), the constants C_1 to C_4 are obtained under the forms:

$$C_1 = 0, \quad (18\text{-a})$$

$$C_2 = -\frac{(W_{out})_n E_1}{\alpha_n}\cdot\frac{(1+\alpha_n t)e^{-\alpha_n t}\sinh\alpha_n t + \alpha_n t\cosh\alpha_n t}{2(\alpha_n t + \sinh\alpha_n t\cosh\alpha_n t)}, \quad (18\text{-b})$$

$$C_3 = -\alpha_n C_2, \quad (18\text{-c})$$

and

$$C_4 = -(W_{out})_n E_1 \frac{(1+\alpha_n t)e^{-\alpha_n t}\alpha_n t \sinh\alpha_n t}{2(\alpha_n t + \sinh\alpha_n t \cosh\alpha_n t)}. \quad (18\text{-d})$$

The deformation W_i of the buffer inner surface is expressed as:

$$W_i = \sum^n (W_i)_n = \sum^n (W_{in})_n \sin\alpha_n x, \quad (19)$$

where

$$(W_i)_n = (W)_{y=o}$$

$$= (W_{out})_n \frac{(1+\alpha_n t)e^{-\alpha_n t}(\sinh\alpha_n t + \alpha_n t \cosh\alpha_n t)}{(\alpha_n t + \sinh\alpha_n t \cosh\alpha_n t)}. \quad (20)$$

The use of equation (20) in equation (19) results in:

$$W_i = \sum^n (W_{out})_n G(\alpha_n t) \sin\alpha_n x, \quad (21)$$

where $G(\alpha_n t)$ is the ratio of inner to outer surface deformation given by:

$$G(\alpha_n t) = \frac{(1+\alpha_n t)e^{-\alpha_n t}(\sinh\alpha_n t + \alpha_n t \cosh\alpha_n t)}{(\alpha_n t + \sinh\alpha_n t \cosh\alpha_n t)}. \quad (22)$$

Fiber Deformation

The fiber deformation W_f, which occurs due to the induced deformation W_i on the buffer inner surface, is defined as the distance on the actual axis from the undeformed axis of the fiber without lateral force and can also be expressed as:

$$W_f = \sum^n (W_f)_n \sin\alpha_n x. \quad (23)$$

By considering the relationship between W_f and W_i, the buffer force F affecting the fiber is given by [6]:

$$F = \sum^n E_1 \alpha_n f(\alpha_n t) d\{(W_{in})_n - (W_f)_n\} \sin\alpha_n x$$

$$- \sum^n E_1 \alpha_n f(\alpha_n t) d (W_f)_n \sin\alpha_n x, \quad (24)$$

where d is the fiber diameter and $f(\alpha_n t)$ is a nondimensional spring constant for the buffer, which indicates the influence of the buffer thickness on the spring effect of the buffer, and is given by:

$$f(\alpha_n t) = \frac{\alpha_n t + \sinh\alpha_n t \cosh\alpha_n t}{2\sinh^2\alpha_n t}. \quad (25)$$

The fiber deformation can be obtained by solving the force equilibrium equation [8]:

$$E_o I_o \frac{d^4 W_f}{dx^4} = F, \quad (26)$$

where E_o is the Young's modulus of the fiber and I_o is its geometrical moment of inertia.

The use of equations (22-24) in equation (26) gives the fiber deformation in the form:

$$(W_f)_n = \frac{E_1 G(\alpha_n t) f(\alpha_n t) d\alpha_n}{E_o I_o \alpha_n^4 (1+\alpha_n t)e^{-\alpha_n t} + 2E_1 f(\alpha_n t) d} (W_{out})_n, \quad (27)$$

from which one can get the fiber deformation W_f in the form:

$$W_f = \sum^n [\frac{E_1 G(\alpha_n t) f(\alpha_n t) d\alpha_n}{E_o I_o \alpha_n^4 (1+\alpha_n t)e^{-\alpha_n t} + 2E_1 f(\alpha_n t) d\alpha_n}] \cdot \frac{AR_2^3 F_n}{E_2 I_2} \sin\alpha_n x. \quad (28)$$

In order to get the excess loss caused by the lateral force, one must first obtain the curvature $\rho(x)$ of the fiber using the formula:

$$\rho(x) = \frac{d^2 W_f}{dx^2} = \sum^n (W_f)_n (1+\alpha_n t)e^{-\alpha_n t}\alpha_n^2 |\sin\alpha_n x|, \quad (29)$$

whose maximum value is:

$$\rho_{max} = \sum^n (W_f)_n (1+\alpha_n t)e^{-\alpha_n t}\alpha_n^2. \quad (30)$$

Finally, the excess loss $\Delta\alpha(x)$ can be estimated, through $\rho(x)$, using the approximation of K. Ishira et al. [6], which gives:

$$\Delta\alpha(x) = 80\ \rho(x)^{1.9}\ \text{dB}. \quad (31)$$

3. RESULTS AND DISCUSSION

The fiber under investigation is characterized by an outer diameter d=125 μm, with Young's modulus E_0=7300 kg.mm^{-2}. The buffer and jacket materials are, respectively, silicon and nylon with corresponding Young's moduli E_1=0.1 and E_2=200 kg.mm^{-2}.

Although the preceding analysis deals with a general form for the lateral pressure acting on the jacketed fiber, the numerical results are performed mainly for illustrating the effect of certain Fourier components of the lateral pressure. The period length P for the lateral pressure, through a fiber of a length l, is defined as:

$$n\pi x/l = 2\pi x/P \quad (32)$$

Equation (27) is used to calculate the ratio of the fiber deformation W_f to the outer deformation of the buffer W_o, and the obtained results are displayed in Figure (2).

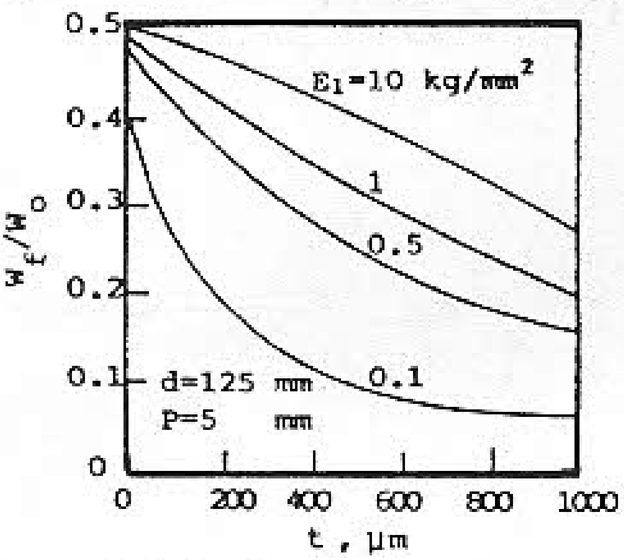

Figure 2. Variation of the fiber deformation to the outer buffer deformation W_f/W_o, with buffer thickness t. (Effect of the buffer Young's modulus E_1).

It can be seen, from Figure (2), that the ratio W_f/W_o is higher for small values of the buffer thickness t, thereafter, it decreases with the buffer thickness. This is a correct result because when the buffer thickness is small, the outside pressure has more influence on the fiber, and when the buffer thickness increases, the outside pressure effect must decrease, and in this case, the buffer is acting as a good shield for the fiber and can protect it from outside. From Figure (2) also, it is noted that the ratio W_f/W_o increases (i.e., the buffer effect decreases) with the buffer Young's modulus E_1. This is expected because, for the same acting pressure and the same value of E_0, the strain in the buffer layer increases with the increase in E_1 while the strain in the fiber remains constant. Consequently, the induced deformation on the fiber must increase.

The variation of the ratio W_f/W_o with the buffer thickness t, for different values of the period length, is illustrated in Figure (3). From this figure, it is clear that the buffer effect decreases with the period length. This can be explained with the aid of Figure (4), where it appears that the ratio of the inner deformation to the outer one, W_i/W_o, increases with the period length for the same buffer thickness. As a result, the fiber deformation will increase as shown in Figure (3). This can also be noted from Figure (5), where the fiber deformation is drawn against the buffer thickness for different period lengths.

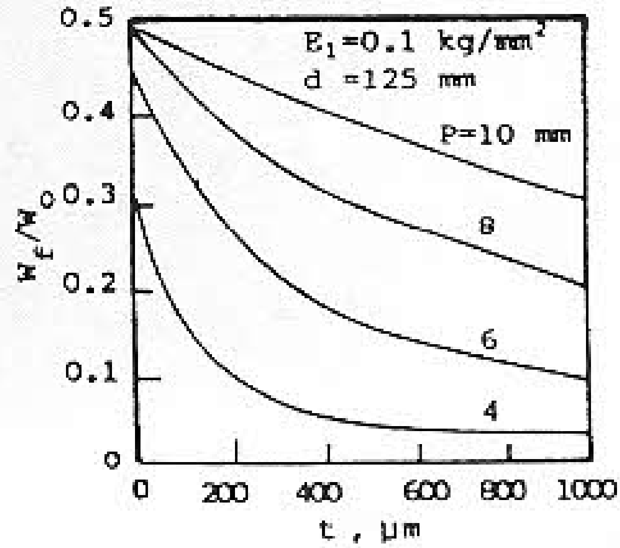

Figure 3. Variation of the fiber deformation to the outer buffer deformation W_f/W_o, with buffer thickness t. (Effect of period length P).

If fibers with greater diameters are to be used, one must expect less fiber deformation, i.e., the buffer effect will increase. This coincides with what we have already obtained as shown in Figure (6).

The effect of the jacket Young's modulus is studied for a lateral pressure F=1 kg/mm. The results obtained are shown in Figure (7), for different values of jacket diameter. It is observed that, the fiber deformation decreases with larger values of both the jacket diameter and its Young's modulus resulting in, as expected, greater suppression for the fiber deformation.

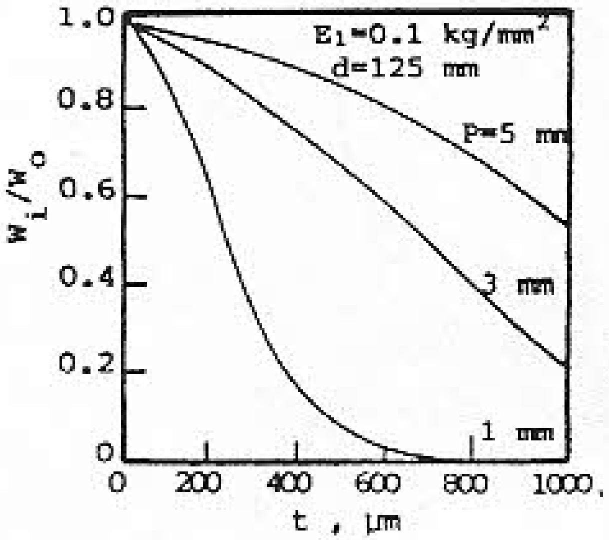

Figure 4. Variation of inner to outer deformation W_i/W_o of buffer layer with its thickness t.

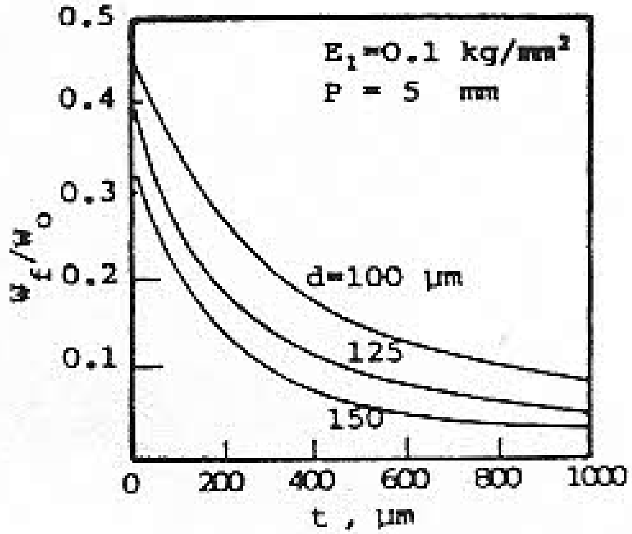

Figure 6. Variation of the fiber deformation to the outer buffer deformation W_f/W_o, with buffer thickness t. (Effect of fiber diameter d).

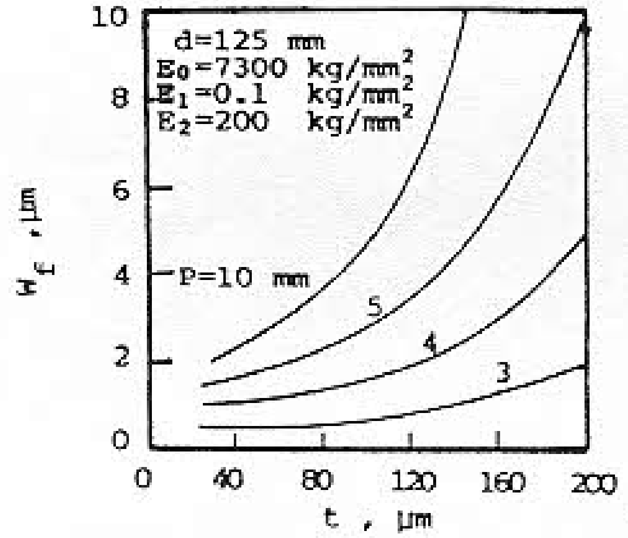

Figure 5. Variation of the fiber deformation W_f with the buffer thickness t.

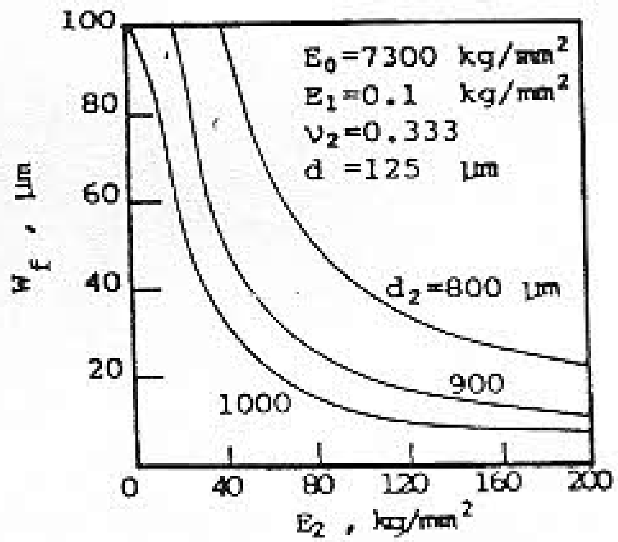

Figure 7. Variation of the fiber deformation W_f with the jacket Young's modulus E_2.

The maximum curvature ρ_{max} of the fiber is calculated through equation (30), and the results are shown in Figure (8) for different values of the buffer Young's modulus. The obtained values of ρ_{max} are used to estimate the excess loss due to the lateral pressure, from equation (31), leading to the results displayed in Figure (9) for an applied pressure of 0.5 kg per period length. A fair agreement is observed, from Figure (9), between the results obtained in the present work and the theoretical and experimental ones [6].

4. CONCLUSION

From the obtained results and the foregoing discussion, one can conclude that the optical fiber deformation induced by a lateral pressure and the corresponding excess loss can be minimized by the following design considerations:

i- Reducing the buffer Young's modulus.

ii- Increasing the jacket Young's modulus.

iii- Increasing the optical fiber diameter.

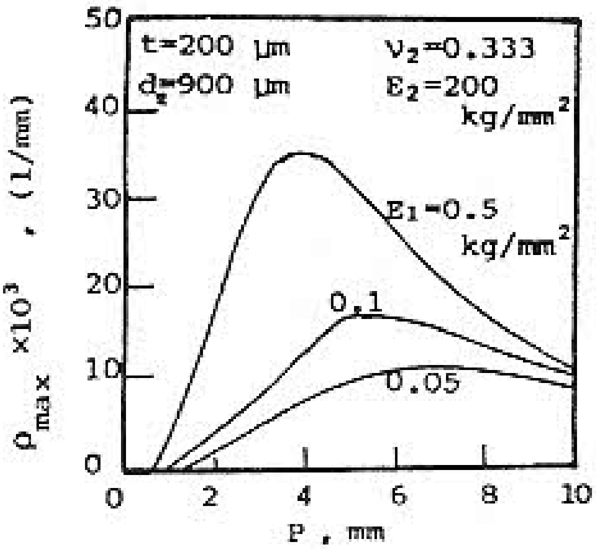

Figure 8. Variation of the fiber bending curvature ρ_{max} with the periodic pressure length P.

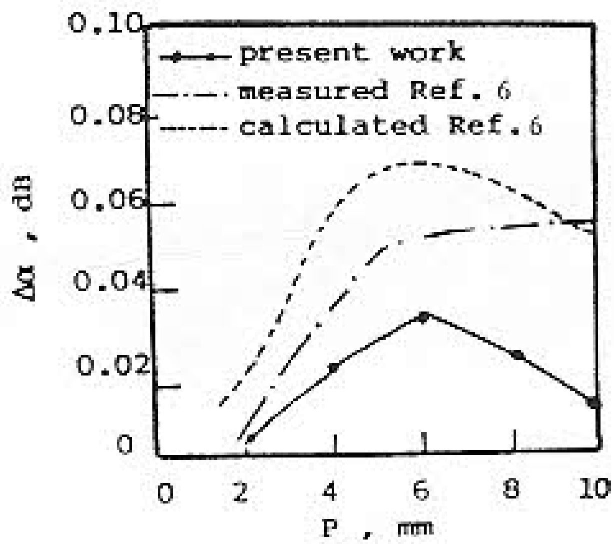

Figure 9. Variation of the excess loss under lateral pressure $\Delta\alpha$ with the periodic pressure length P.

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