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ACCOUNTING FOR STRAIGHT PARTS EFFECTS ON ELBOW'S FLEXIBILITIES IN A BEAM TYPE FINITE ELEMENT PROGRAM

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An extension of Von Karman's theory is applied to the calculations of the flexibility factor of a pipe bend terminated by a straight part or a flange. This analysis is restricted to the linear elastic deformation behaviour under in plane bending. Analytical solutions are given for the propagation of ovalization in the elbow and in the straight part.

Considering the response of the piping structures, we note that the ovalization of the piping systems are reduced significantly when the straight parts or flanges effects are included. The results are presented in terms of global as well local flexibility factors. They have been compared to numerical results obtained by shell type finite elements method.

A complete piping system is analyzed, for economical reasons, with a beam type approach. Also, we show how it is possible to take into account on elbow's flexibilities the straight parts effects by means of flexibilities factors introduced in a beam type element. We have implemented this method in the computer program TEDEL. In some specific geometrical features, we compare solutions using shell type elements and our formulation.

1. Introduction

The elastic analysis of complete piping systems is currently performed for design purposes by using a standard beam type program, where bending properties are modified by means of the well-known flexibility factors for elbows. The reason for these factors is that contrary to the classical beam theory, the pipe bend cross section is deformable and tends to ovalize under bending moments. The theory has been first developped by Von Karman [1] and then refined by many authors. However the corresponding flexibility factors are derived for elbows considered as a part of an axi-symmetrical torus. The straight parts or flanges at the end of the elbow will reduce the ovalization and thus increase the stiffness of the elbow. Some work has been done on this problem using either experimental (Table 1), numerical (Table 2 and reference [8]) or analytical (Table 3) approaches. There is still much to do in order to investigate the influence of the various geometrical parameters :

$$\lambda = \frac{eR}{r^2}$$

where e = pipe thickness, R = bend radius, r = pipe radius,

$\mu = \frac{r}{R}$

ν = Poisson's ratio

α = half-bend angle

ℓ = length of the straight part, etc. .... .

and the influence of material and geometrical non linearities (plasticity, creep, large displacements, etc. ...).

The aim of this paper is to present a first approximation method which enables accounting for straight parts effect on elbows under in plane-bending, in a beam type program.

Some results are also mentioned for the case of an elbow terminated by flanges.

2. Description of the method

A typical geometry of the problem under investigation is shown on figure 1. The curvilinear abscisse x is measured along the mid-line, starting from the mid-bend.

As mentioned in reference [22], the ovalization varies continuously along the elbow and the straight part, whereas the curvature variation is discontinuous at the elbow-straight part connection C (see figure 1). Therefore two methods can be proposed for the definition of a modified elbow stiffness :

- A global method, by considering a global flexibility factor, constant over the elbow, defined by :

$$k_G = \frac{\Psi(x_c)}{\Psi_S(x_c)}$$

where $\Psi(x_c)$ denotes the cross-section rotation at the end of the bend, and $\Psi_S(x_c)$ denotes the end rotation of straight pipe of length x_c, subjected to the same bending moment M, i.e. :

$$\Psi_S(x_c) = \frac{M}{EI} x_c$$

EI = bending stiffness of a straight pipe with same characteristics.

Noting k_{axs} the usual flexibility factor determined for an axi-symmetric torus, the variation of the ratio $\frac{k_G}{k_{axs}}$ versus α has been calculated for $\lambda = 0.5$, $\mu = 0.2$, $\nu = 0.3$ using elementary solutions for the propagation of ovalization along straight pipes and elbows, derived in reference [22]. Results are shown on figure 2. It may be noted that the value for $\alpha = 0$ corresponds to the flexibility of an inextensible straight pipe (i.e. no circumferential strain allowed).

- A local method, by considering a flexibility factor which varies along the elbow, defined by :

$$k_\ell(x) = \frac{EI}{M} \frac{d\gamma}{dx}(x)$$

These functions have been calculated for the elbow previously defined and for various bend angles. They are shown on figure 3.

It may be noted that in the case of a 180° bend, the local flexibility at mid-bend is superior to the usual k_{360} ; this must be due to the fact that shear strains have not been neglected.

With this method, it is possible to prescribe different flexibility factors for the various finite elements of the bend mesh. In the straight parts, the flexibility factor remains unity.

For a given elbow, it is possible to calculate k_G and $k_\ell(x)$ from published analytical solutions or if they are not available, to compute them by a shell finite element program. In case of a monotonous simple loading, the method can be extended to the calculation of flexibility factors accounting for plasticity and large displacements, and varying with loading. An application could be the limit analysis of a complete piping system.

When local stresses are required, a similar work must be done for the stress intensification factors and it is clear that only the local approach is realistic.

3. First approximation method

This method consists in assuming that the curves $\frac{k_\ell(x)}{k_{360}}$ calculated for some specific values of the parameters and particularly $\lambda = 0.5$, give a good description of the variation of the flexibility factor. It is only a first approximation since these curves should be calculated for any value of the various parameters λ, μ, ν etc. ... . The error can be estimated by performing a shell finite element calculation. This has been done in particular on five pipe bends with straight parts (see figure 1), three of such assemblies being representative of a PWR primary circuit.

3.1 90° pipe bend with following characteristics

$e = 0.3333$	$\nu = 0.3$
$r = 10$	$E = 20{,}000$
$R = 30$	$\lambda = 0.1$
$\ell = 100$	

The cross section rotations have been calculated using three approaches :

a) shell finite element calculation,

b) beam calculation using k_{360}

c) beam calculation using $k_\ell(x)$

The beam calculations and shell calculations have been performed using the TEDEL [21] and BILBO [23] programs of the CEASEMT system [20]. Results are plotted on figure 4. In this case, the agreement between the proposed method and the shell solution is excellent.

It is interesting to note that the ratio of the cross sections at the end of the elbow between calculations c and b is very close to the ratio $\frac{kg}{k_{360}}$, which shows that in this case, the use of a uniform flexibility factor kg would lead to an excellent solution too.

3.2 Three values of bend angle have been investigated for the following parameters
$e = 70$, $r = 435$, $R = 1300$, $\nu = 0.3$, $\ell = 4000$. Therefore $\lambda = 0.48$.

Bend angle values were : $2\alpha = 90°$, $50°$, $22°5$.

Results are shown on figures 5, 6, 7.

It can be seen that the agreement is better for lower bend angles.

3.3 In order to estimate the validity of the method for low λ values, a calculation has been performed on the small angle bend ($2\alpha = 22°5$) with $\lambda = 0.1$. Again, the agreement is very good (see figure 8).

3.4 Remarks

It can be observed that the proposed method tends to overpredict the flexibility of the elbow for λ close to 0.5 and for large bend angles. This effect diminishes with λ because the number of terms of the Fourier series considered in the analytical solution becomes insufficient, and with the bend angle because of the inextensibility hypothesis assumed in the straight pipe, which has an increasing influence on the elbow.

The improvement of the analytical solution does not present any theoretical difficulties but requires an important amount of calculations.

4. Conclusion

The calculations performed using local flexibilities derived from some analytical solutions of propagation of ovalization are in a fairly good agreement with shell finite elements calculations. The main advantage of the method is to be simple to use and cheap. Of course, it must be further validated over a large range of parameters values, and improved. Results are already available for bends terminated by flanges.

New developments must be done for other configurations (short straight parts, reversed elbows, etc.) and other types of loadings (out of plane bending, internal pressure, etc. ..).

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TABLE 1 - EXPERIMENTAL WORK

AUTHORS	REF.	BEND ANGLE	END EFFECTS			LOADS		
			Flanges	straight parts	reversed elbows	in plane	out of plane	pressure
SYMONDS PARDUE	[2]	90°	+	+		+		
PARDUE VIGNESS	[3]	45°, 90°, 180°	+	+		+	+	
IMAMASA URAGAMI	[4]	90°		+		+	+	+
		40°, 50°, 60°, 90°	+	+		+	+	+
FINDLAY SPENCE	[5]	45°, 90°, 180°	+			+		
BROUARD TREMBLAIS VRILLON	[6]	90°	+	+		+		
		180°	+	+		+	+	
BROUARD MILLARD TOMASSIAN	[7]	90°		+		+		
		180°		+		+		

TABLE 2 - COMPUTATIONAL WORK

AUTHORS	REF.	BEND ANGLE	END EFFECTS			LOADS		
			Flanges	straight parts	reversed elbows	in plane bending	out of plane bending	pressure
KANO et al.	[9]	90°		+		+	+	
SOBEL	[10]	90°		+		+		
NATARAJAN BLOMFIELD	[11]	90°	+	+		+		
		30°, 90°, 180°		+		+		
		90°			+	+		
WRIGHT RODABAUGH THAILER	[12]	50° with variable thickness		+		+		
RODABAUGH ISKANDER MOORE	[13]	45°, 90°, 180°		+		+	+	
OHTSUBO WATANABE	[14]	90°		+		+	+	
NATARAJAN MIRZA	[19]	from -10° to 90°		+			+	
		90°	+	+			+	

TABLE 3 - ANALYTICAL WORK

AUTHORS	REF.	BEND ANGLE	END EFFECTS			LOADS		
			Flanges	straight parts	reversed elbows	in plane	out of plane	pressure
THAILER CHENG	[15]	180°	+			+		
FINDLAY SPENCE	[16]	ANY	+			+		
THOMSON SPENCE	[18]	ANY	+	+		+		
WHATHAM THOMPSON	[17]	50°, 180°	+	+		+		+
MILLARD ROCHE	[22]	ANY	+	+		+		

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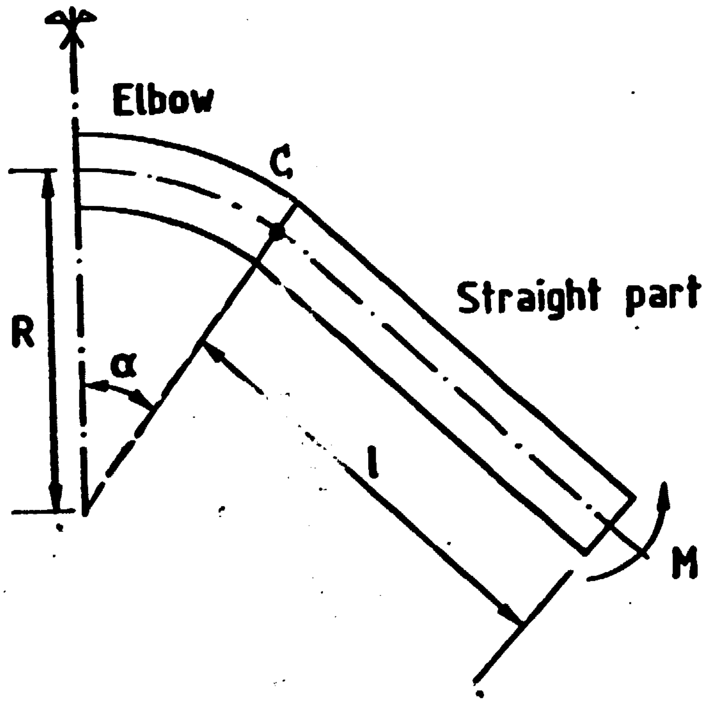

Fig. 1

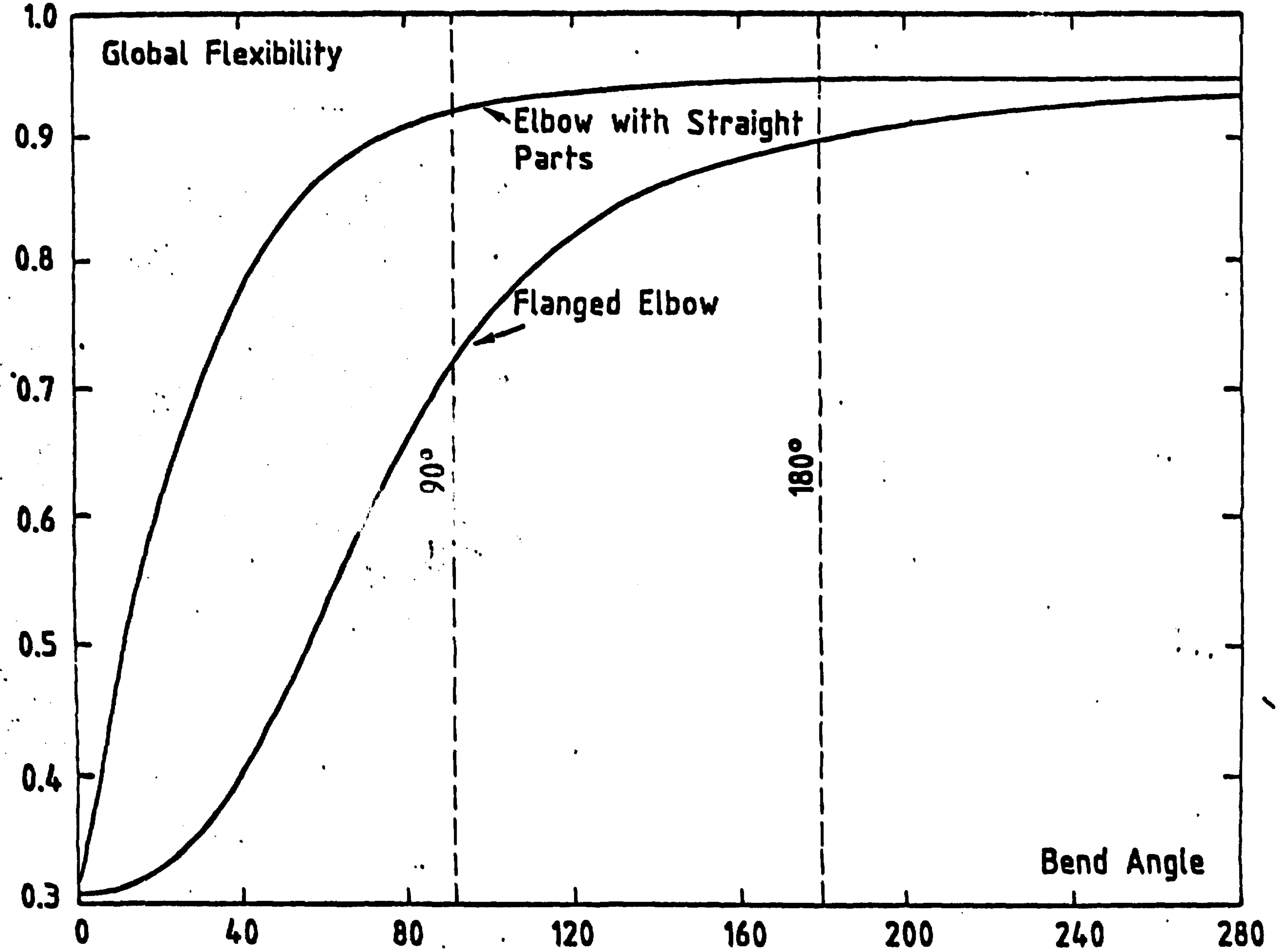
Global Flexibility
Elbow with Straight Parts
Flanged Elbow
90°
180°
Bend Angle
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
40
80
120
160
200
240
280

Figure 2

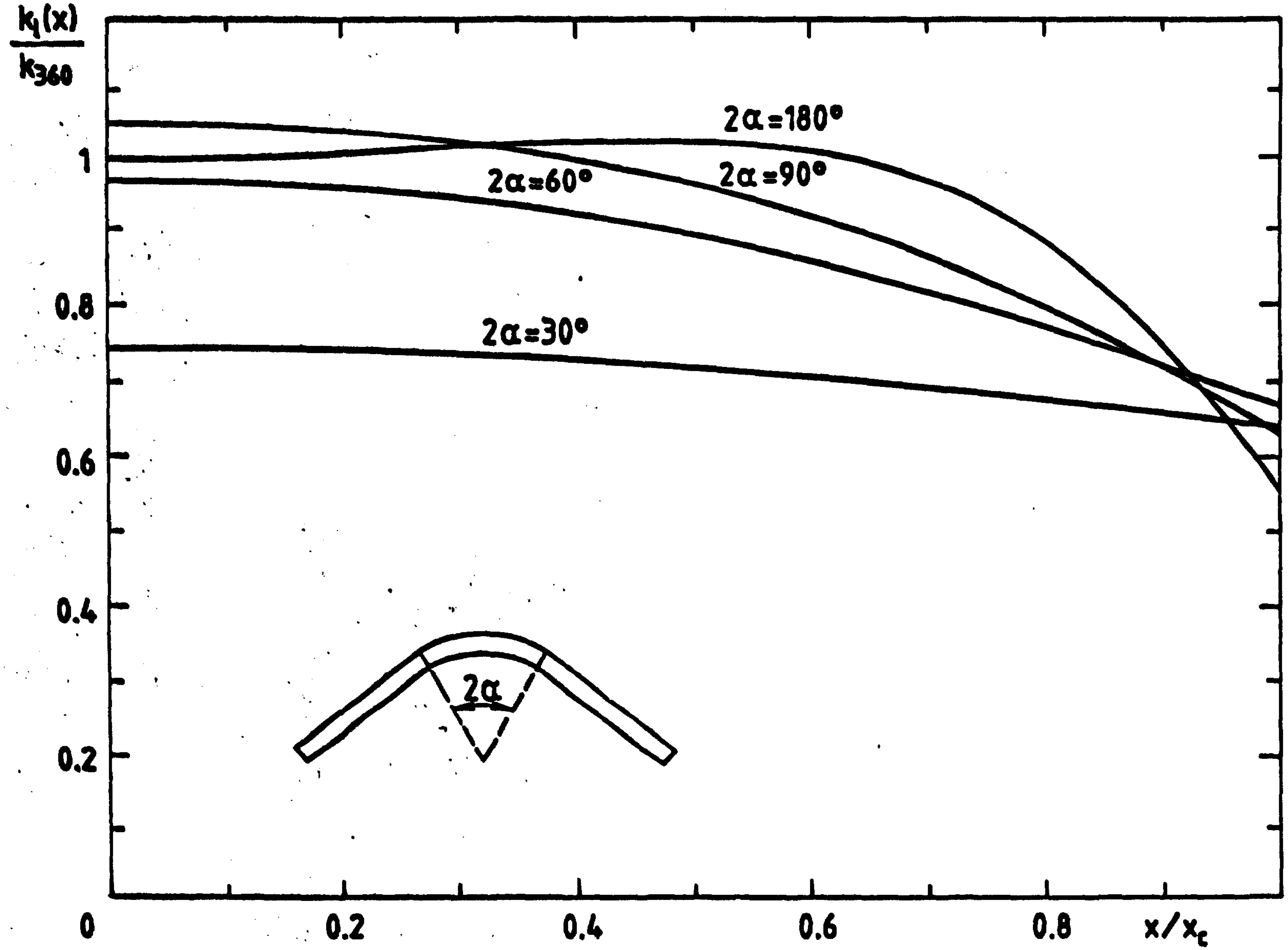

Fig. 3 - Local flexibility

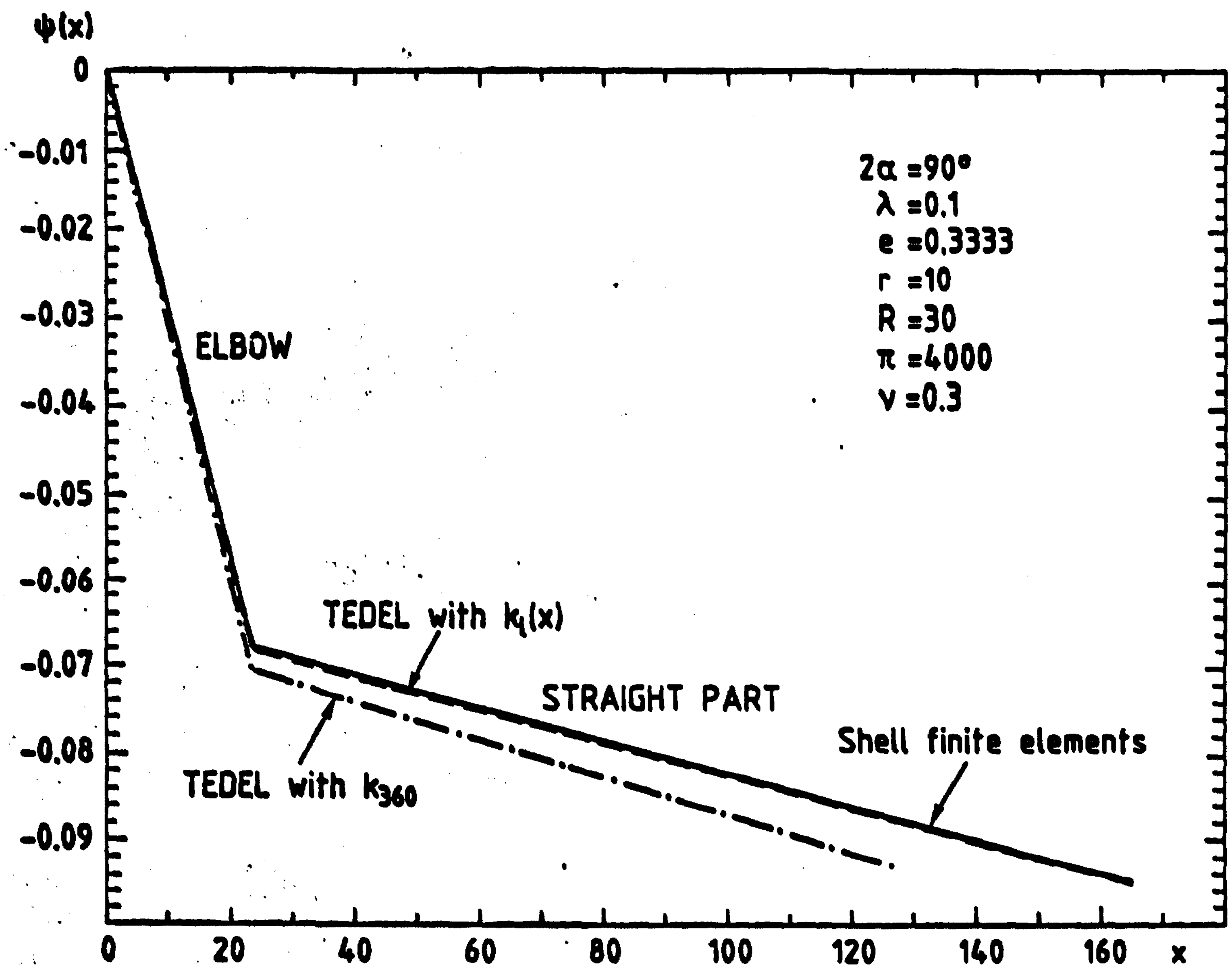

Fig. 4 - Cross-section rotation versus curvilinear abscissa

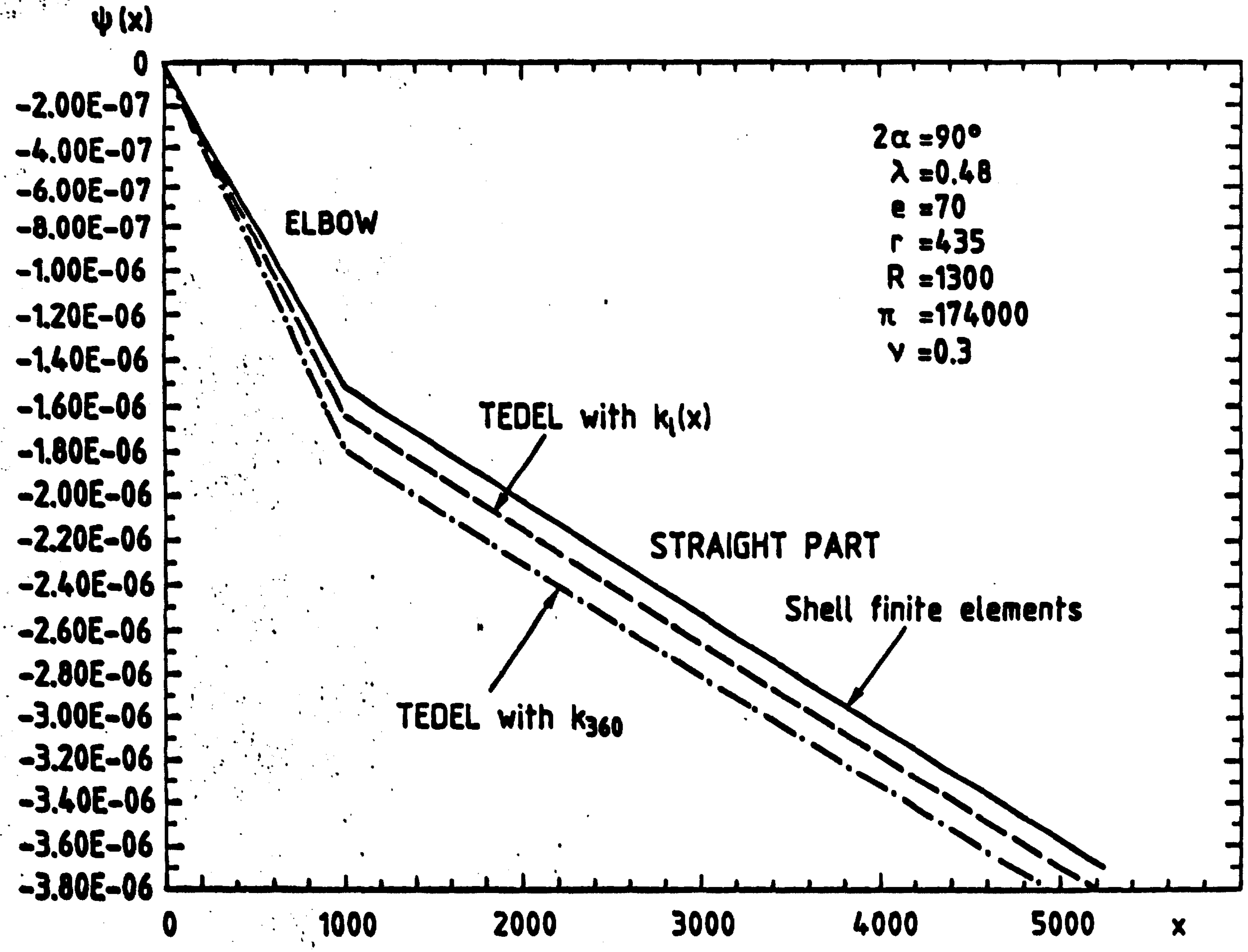

Fig. 5 - Cross-section rotation versus curvilinear abscissa

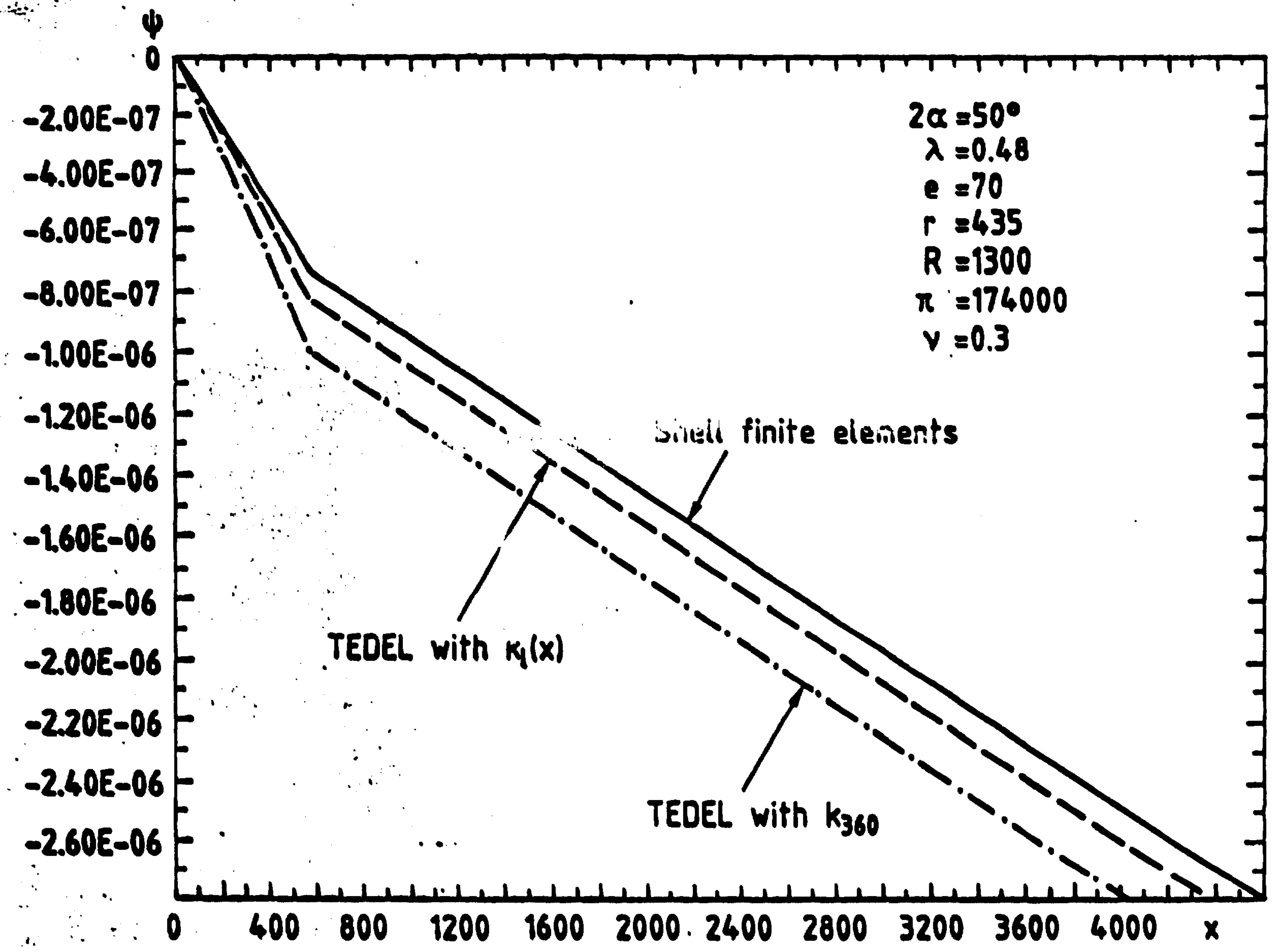

Fig. 6 – Cross-section rotation versus curvilinear abscissa

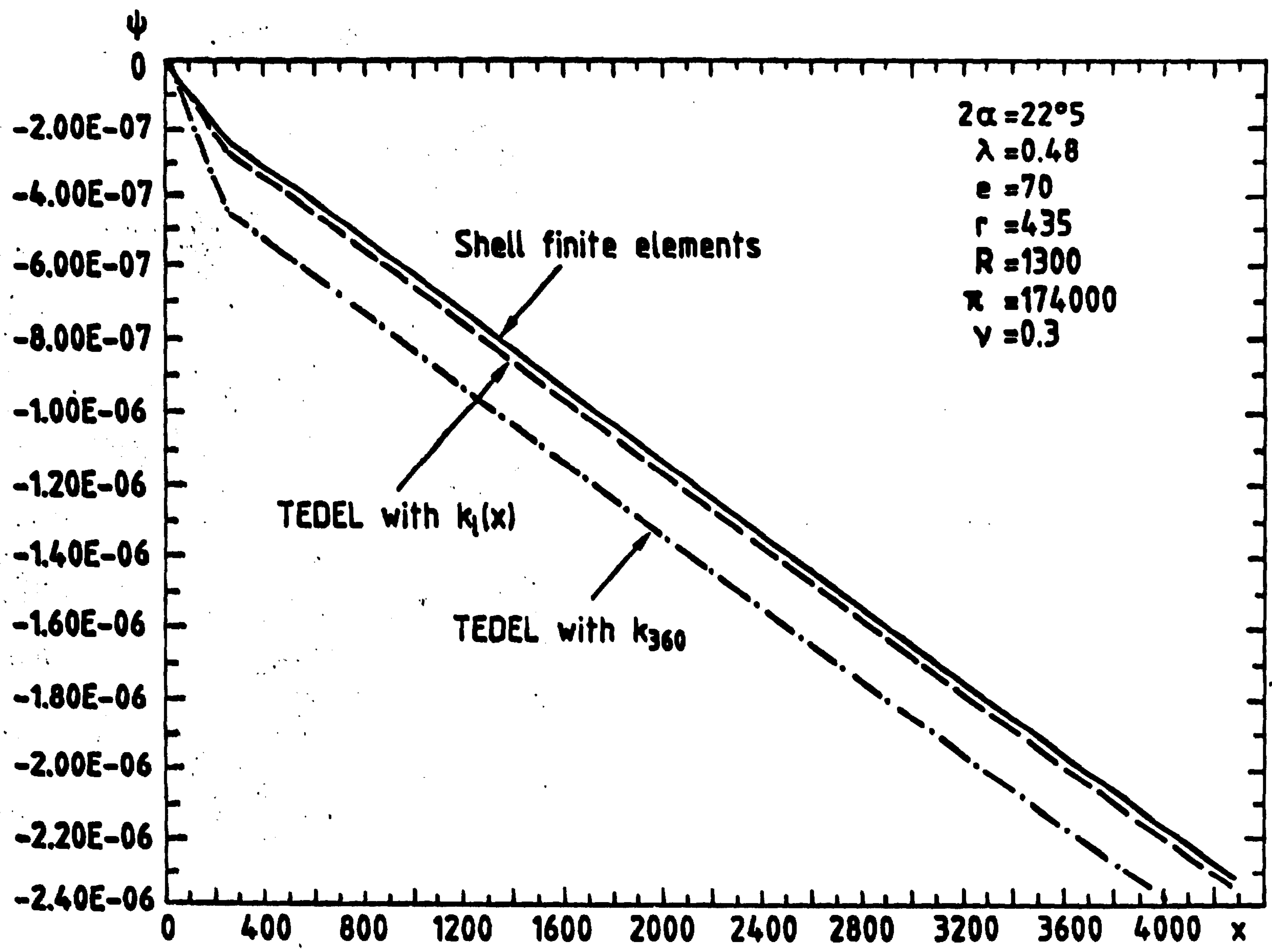

Fig. 7 - Cross-section rotation versus curvilinear abscissa

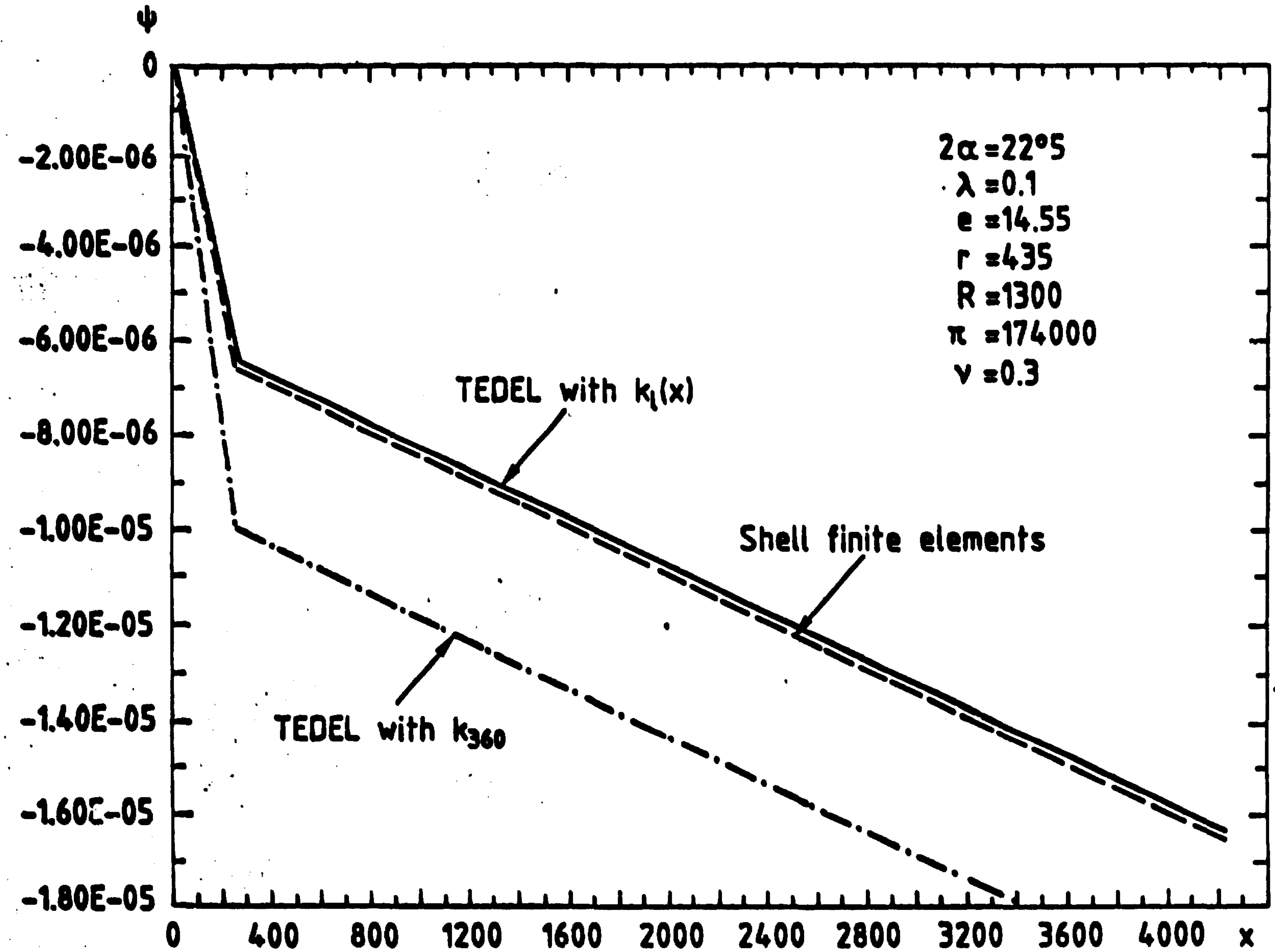

Fig. 8 - Cross-section rotation versus curvilinear abscissa