# Design of cylindrical plastic pipe linings to resist buckling due to collapse pressures

**J. C. Boot***

Flexible (non-bonded) polymeric sewer linings are used extensively to renovate both gravity and pressure pipes. Linings for both types of pipe are subject to collapse pressures, and in the case of gravity pipes this is the dominant source of loading; the efficient design of linings to sustain collapse pressures is therefore an important problem. In this paper, the buckling of an ideal thin-walled elastic lining in a rigid cylindrical cavity is first presented as a simple closed form solution, and the effect of a representative small imperfection shown to be significant. The different types of imperfection that can be encountered in practical lined pipe systems are identified, and the situations in which each can arise are discussed. A generalised procedure for obtaining the structural imperfections in, and hence buckling capacities of, practical systems is then presented and two example applications are used to illustrate its application in specific situations.

**Keywords:** Pipes, Linings, Design, Buckling

## Introduction

The requirement to structurally upgrade pipe systems for both pressure and gravity applications is a common problem for pipeline engineers internationally. In this respect, renovation of the existing pipe can minimise both cost and disruption in comparison to renewal of the pipe in trench. In particular, the insertion of a flexible (i.e. debonded) close-fit polymeric lining[1] has become very popular for both technical and financial reasons, and a range of lining materials and insertion techniques has been available for about 20 years.[2,3] Despite this, structural design guidelines currently in use for both types of system[1,4] were developed before their behaviour had been extensively researched, and have been extensively criticised in the literature in recent years.[5,6]

In the case of a gravity flow system (e.g. sewer), the pipe is rarely under internal pressure, and external loading owing to soil/pipe interaction and groundwater are dominant. Nevertheless, the process of host pipe deterioration is very rarely instigated by excessive superimposed loading, but rather by one of a number of possible internal durability problems. Whatever the precise cause, the eventual result in the case of nominally circular pipe[1] is development of cracks at the invert, soffit and springings, resulting in an increase and decrease in the horizontal and vertical diameters, respectively, such that the pipe begins to adopt a slightly oval cross-section. Whether the pipe was originally flexible (e.g. brick construction) or rigid (e.g. concrete or vitrified clay), the pipe–soil system at this stage is significantly stronger than previously owing to the increased passive resistance that can be mobilised in the soil.[5]

Thus, the initial stages in the structural deterioration of a gravity pipe are far from catastrophic; however, gradual loss of soil support because of continual infiltration of groundwater can now occur, exacerbated by backwash during times of flood. This in turn causes a progressive ovalling of the pipe cross-section, eventually leading to collapse unless steps are taken to arrest the problem. However, provided remedial action is taken to restore hydraulic integrity before excessive deformation (say 10%) occurs, the system is still structurally sound and can be re-stabilised without the need for any strengthening.[1] Any significant voids in the backfill will be apparent from large local deformations/damage and can be grouted using proprietary techniques; continuing compaction and consolidation will cause any small voids at the pipe/soil interface to migrate to the surface following renovation.[5]

The prime function of a flexible lining is therefore to provide a waterproof membrane on the bore of the pipe, thus returning the pipe to a state of hydraulic integrity, and enabling the original soil–pipe system to maintain a state of structural stability.[7] Under the conditions described above, structural performance of the lining is dominated by its ability to sustain the external head of groundwater pressure (that must be assumed to develop once hydraulic integrity is restored) within the confines of the host pipe. The vast majority of pipes requiring renovation have a nominally circular cross-section, but subject to a relatively small ($\leqslant 10\%$) ovality. Thus renovation is undertaken with a thin-walled lining, and liner buckling is the dominant structural design criterion.

In the case of a pressure pipe, bursting resistance as a result of internal pressure is normally the dominant

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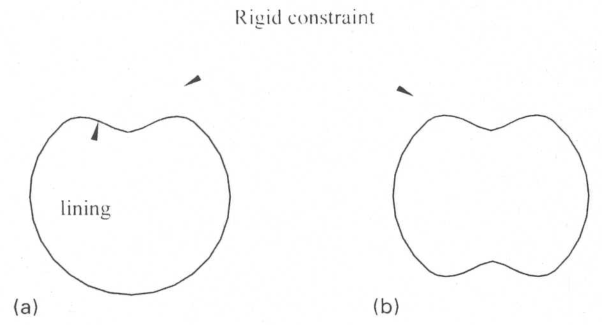
© 2005 Institute of Materials, Minerals and Mining
Published by Maney on behalf of the Institute
Received 1 February 2005; accepted 16 February 2005
DOI 10.1179/174328905X29712



*a* single lobe deformation; *b* double lobe deformation
**1 Fundamental modes of lining behaviour**

source of loading on a flexible lining, which must therefore be designed to sustain the stresses so induced.[8,9] Nevertheless, a pressure pipe must also be able to perform adequately as a gravity pipe before it enters service and during periods of maintenance. In addition, negative internal pressures can be encountered due to surge conditions occurring during service. It is therefore also, in general, necessary to design pressure pipe linings with adequate capacity to resist collapse owing to buckling in these situations.

Negative internal pressure during service is a dynamic (short-term) problem, which can be assumed to occur under elastic conditions. When subject to loading over any significant period of time, current generation pipe grade plastics creep under load, thus causing the deformations to gradually increase. Nevertheless, assuming that the groundwater pressure rapidly builds up to a constant long term value, it has been shown that elastic theory incorporating a suitably defined secant modulus can be used to assess liner buckling capability when constrained to deform within the confines of the host pipe[10,11] to an acceptable level of accuracy. In addition, it is known[5,12] that linings installed by different methods in different categories of pipe are subject to varying amounts and types of imperfection, and that liner buckling capacity can be very sensitive to small variations in the total perturbation from a nominally circular cross-sectional geometry. In the sequel, the implications of these observations will be investigated so as to identify a generalised design procedure in respect of liner collapse which takes due account of both the installation and application dependence of the behaviour of any particular lining.

## Buckling of elastic lining in a rigid constraint of nominally circular cross-section

The theoretical buckling pressure of a tight-fitting elastic lining in a perfectly rigid circular constraint has been established by Glock[13] and Boot.[10] At the critical pressure, the lining will buckle into either the single lobe shape of Fig. 1*a* or the two lobe shape of Fig. 1*b*. In either case, the buckling pressure can be expressed as

$$p_{\mathrm{crit}} = kE'({}^{D}/_{t})^{\mathrm{m}} \tag{1}$$

where $E'=E$ for plane stress or $E/(1-\nu^2)$ for plane strain (normally assumed for design purposes) $E$=elastic modulus, $\nu$=Poisson's ratio, $D$=lining mean diameter, $t$=lining thickness, $m=-2{\cdot}2$ and $k=1$ and $1{\cdot}323$ for single and double lobe buckling, respectively.

Which of these buckling modes is obtained depends essentially on the nature of the imperfections in the system. In the case of a geometrically perfect lining in a perfectly circular constraint, symmetry enforces two lobe behaviour. This will also be obtained[10] in an imperfect system which is dominantly symmetrical, otherwise the imperfect system will demonstrate single lobe behaviour.

Equation (1) can be re-expressed as a linear function in the form

$$\log_{10}\left(\frac{p_{\mathrm{crit}}}{E'}\right) = m\log_{10}\left(\frac{D}{t}\right) + c \tag{2}$$

where $c=\log_{10}k$ and all other terms retain their meanings as before.

Boot[10] has shown that, when subject to any specified level of gap imperfection, the general form of equation (2) remains valid except that $m$ and $c$ are now functions of the magnitude of the imperfection. Thus, for example, at zero gap imperfection, $m$ and $c$ are as defined above for perfect geometry, while at infinite gap (the unconstrained case), $m=-3$, $c=\log_{10}2$; substituting these values of $m$ and $c$ yields the classical result[14] for an unconstrained elastic ring.

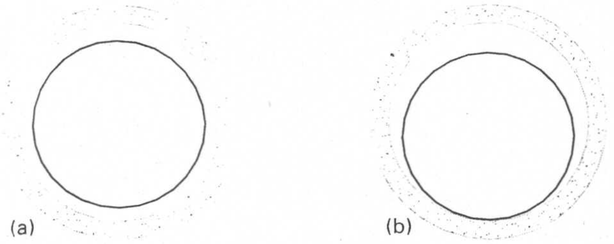
For intermediate values of gap, the values of $m$ and $c$ quoted in Table 1 can be obtained,[10] where IOD= imperfection on diameter=2×gap/$D$ for two lobe behaviour and maximum gap/$D$ for single lobe behaviour (Fig. 2).

For values of gap >5% radius, the solution rapidly approaches the unconstrained buckling pressure. Equation (2) and Table 1 show that at $D/t=75$, a representative small imperfection comprising a symmetrical gap of only 1% of the lining radius will reduce the buckling capacity of the perfect system by 50%. Thus, it is important to be able to identify the imperfections in practical systems and accurately quantify their effects if efficient design of flexible pipe linings is to be undertaken.

In this respect, since the effect of all small imperfections (i.e. those that do not invalidate the assumed buckling criterion) is qualitatively the same, then it is readily verified[12] that the general form of equation (2) is valid for all types of geometric imperfection, with the quantitative effect of the overall imperfection defined by the numerical values of $m$ and $c$. Thus, the different types of imperfection that can be encountered in practical pipe lining systems are now discussed and their effects quantified.

**Table 1 Parameters ($m$, $c$) defining equation (1) for a range of symmetrical and asymmetrical gap configurations**

| | Two lobe solution | | One lobe solution | |
|---|---|---|---|---|
| *IOD, %* | *m* | *c* | *m* | *c* |
| 0·45 | −2·506 | 0·545 | −2·506 | 0·424 |
| 1·0 | −2·706 | 0·786 | −2·706 | 0·669 |
| 2·0 | −2·853 | 0·912 | −2·853 | 0·783 |
| 3·0 | −2·916 | 0·918 | −2·916 | 0·802 |
| 5·0 | −2·959 | 0·823 | −2·959 | 0·740 |

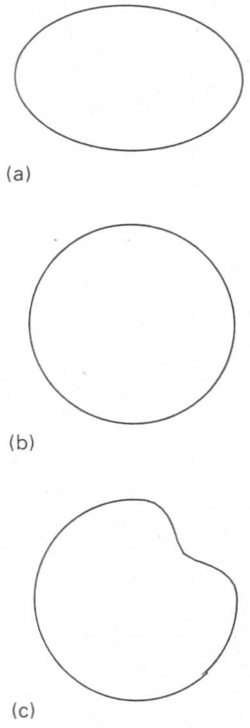


*a* symmetrical gap; *b* asymmetrical gap
**2 Different classifications of gap**

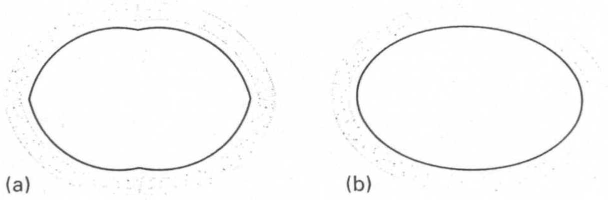
## Imperfection study

Geometrically, essentially three different types of imperfection can be identified, as indicated in Fig. 3, which are relevant to liner design. The basic mode of gravity pipe deterioration, as described previously, leads to a small ovality imperfection in the system to be lined as shown in Fig. 3*a*. Any lack of fit between the host pipe and lining gives rise to a gap imperfection between the two as delineated in Fig. 3*b*. Ovality and gap are global imperfections because they affect the whole cross-section of the system. Figure 3*c* illustrates a local imperfection (i.e. one which affects only part of the lining perimeter) in the form of a small single lobe in the lining. Any multi-lobe imperfection can therefore be considered as the sum of a number of independent single lobes.

Considering each of the three types of imperfection identified in Fig. 3 in turn, two different types of ovality can be identified. The dominant ovality in a pipe cross-section which cannot sustain any tension (e.g. a brick and mortar pipe) or which fails in a brittle manner (e.g. a concrete or vitrified clay pipe) is invariably caused by the formation of cracks at the crown, invert, and springings of an initially circular pipe, and is the normal instigator of gravity pipe system deterioration. This type of ovality is therefore formed from the four pipe quadrants pivoting as indicated in Fig. 4*a*, with discontinuous slopes where adjacent quadrants connect. Alternatively, any out-of-roundness of the host pipe because of manufacturing tolerances will take the form of an essentially elliptical geometry as shown in Fig. 4*b*; this type of imperfection is also obtained when diametrically compressing and lining an initially circular steel pipe in order to obtain slightly oval specimens for laboratory testing. It is readily demonstrated (by finite element analysis, etc.) that a given amount of quadrant ovality is a significantly more severe imperfection than an equivalent degree of elliptical ovality, and it is important to recognise this when developing design procedures, or correlating mathematical and physical test results. Whichever type of ovality pertains in a particular situation, it is evident from this discussion that ovality is an imperfection in the *system* being lined and is independent of the type of lining and the technique used to install it.



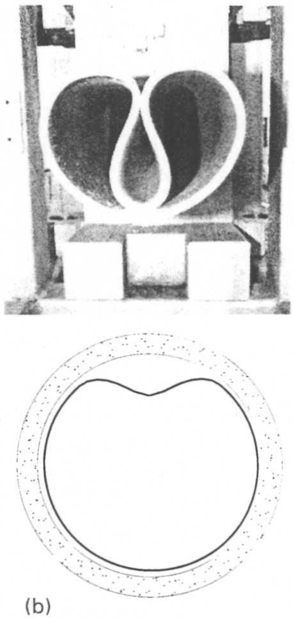
*a* host pipe ovality; *b* lining/host pipe gap; *c* local lining imperfection
**3 Three independent categories of geometrical deformation**



*a* quadrant ovality; *b* elliptical ovality
**4 Different classifications of ovality**

Two different types of annular gap between the host pipe and lining can also be identified. If the gap is of the order of the roughness of the pipe-lining contact surface, it will tend to be very small in comparison to the major dimensions of the system and three-dimensionally discontinuous. This combination of circumstances will result in an approximately symmetrical gap configuration as shown in Fig. 2*a*. As the ratio of the gap/lining diameter increases, then gravity or buoyancy effects become dominant, and the initial gap will be eccentric as illustrated in Fig. 2*b*. Clearly, therefore, the magnitude and configuration of any initial gap between the lining and host pipe is essentially a *characteristic* of the lining procedure and is independent of the *system* being lined.

The occasional displaced brick in a host pipe is a three-dimensionally local imperfection which can redistribute load to adjacent stronger cross-sections. However, a line of displaced bricks in the crown can, in principle, induce a local imperfection as shown in Fig. 3*c*. The displaced bricks are caused by the soil arching round the pipe, thus unloading the arch in compression. Under these conditions, there is normally no downwards vertical loading on the displaced bricks, and lining insertion will displace them back towards their original position. Occasionally the displaced bricks at the crown can become reloaded (due for example, to the subsequent development of a water table), in which case the local *system* imperfection (i.e. the imperfection in the *system* being lined) can be simulated by increasing the specified quadrant ovality. This is because quadrant ovality includes a significant component of local imperfection; indeed it is qualitatively similar to a local imperfection superimposed on elliptical ovality.



*a* factory produced pipe folded for insertion (courtesy of Subterra); *b* reversion leaves small local imperfection in lining

**5 Lining insertion technique resulting in local characteristic imperfection**

A second source of local *system* imperfection could be a severe loss of smoothness of the host pipe inner surface. However, this would have to be both longitudinally continuous and located so as to compound the deflected lobe (i.e. be at the crown or invert) to be significant. In this extremely unlikely event, again the effect can be included by increasing the specified quadrant ovality.

The Subline® technique[15] for the installation of a close-fitting factory produced polyethylene lining involves the on-site folding of a welded pipe string as indicated in Fig. 5*a*. The pipe is then held in its folded form using steel bands and winched into the host pipe. Subsequent application of internal pressure then breaks the steel bands and reverts the liner pipe towards its original circular form; nevertheless, the lining will exhibit a small local imperfection after installation as delineated in Fig. 5*b*, which this time is purely a *characteristic* of the installation procedure.

Equation (2) can be expressed in the form

$$\log {}^{p_{\mathrm{crit}}}/_{E'} = f(\log {}^{D}/_{t}, \delta_{\mathrm{g}}) \tag{3}$$

where $\delta_{\mathrm{g}}$ is the annular gap imperfection, expressed in appropriate non-dimensional form.[10] Now since the effect of all small imperfections is qualitatively the same (i.e. to reduce $p_{\mathrm{crit}}$), it follows that the general case can be similarly expressed as

$$\log {}^{p_{\mathrm{crit}}}/_{E'} = f(\log {}^{D}/_{t}, \delta_{\mathrm{t}}) \tag{4}$$

with $\delta_{\mathrm{t}}$ (the total non-dimensional imperfection) a combination of all the possible sources of imperfection and therefore, on the basis of the argument presented above, given by

$$\delta_{\mathrm{t}} = \frac{\text{symm. gap}}{R} + \frac{\text{asymm. gap}}{D} + \text{quadrant ovality} + \text{elliptical ovality} + \frac{\text{local imperfection}}{D} \tag{5}$$

where ovality$=(D_{\max}-D_{\min})/D$, $D=(D_{\max}+D_{\min})/2$, and $D_{\max}$, $D_{\min}$ are the major and minor principal diameters of the ellipse, respectively.[4]

Identification of an appropriate numerical value to adopt for each term in equation (5) is aided by noting that these can be classified as either:

(i) Imperfections which are essentially a function of the *system* being lined
(ii) Imperfections that are *characteristic* of the lining technique being used.

Thus, the total imperfection in any given system can be considered as being comprised of independent *system* and *characteristic* components, and the most appropriate method of obtaining the required design parameters (normally lining thickness) thence obtained.

## Example applications

### Buckling capacities of polyethylene linings for pressure pipe installed using Rolldown technique

Rolldown[16] is an on-site procedure for the installation of close-fit polyethylene linings: a number of factory produced polyethylene pipes are welded together into a continuous string, which is then pushed through a series of rollers at ambient temperature to reduce its diameter (and hence increasing its length and thickness accordingly) by about 10% through cold plastic working. The liner pipe is then winched into the host pipe and reverted to obtain a close fit between the two by cold work using water pressure at ambient temperature.

The dimensions of the liner pipe and Rolldown procedure are normally chosen to obtain a minimum initial lack of fit of about 5% on diameter between the host pipe and lining at the time of installation.[16] Then, assuming the former to be infinitely rigid in comparison to the latter, elastic recovery of the lining following reversion will mean there is a small initial gap of the order of 0·5% diameter (yield strain of PE ≈ 10%) in the unpressurised system. Although creep as a result of long term service pressure may reduce this, variations and uncertainties in the system dimensions and mechanical properties suggest that in the absence of better information, an initial asymmetrical gap of 1% is an appropriate assumption for the evaluation of liner buckling capacity. Rolldown is normally used for the rehabilitation of water and gas pressure pipe, which will only be subject to ovality as a result of manufacturing tolerances, and it is readily demonstrated (e.g. by finite element analysis[5,12]) that this is a negligible imperfection in comparison to the assumed gap. Consequently, equations (4) and (5) reduce to equation (1) for the problem under consideration with $m$ and $c$ obtained from Table 1 for single lobe deformation ($m=-2{\cdot}706$, $c=0{\cdot}669$ for 1% asymmetrical gap). $E$ can be taken as the long term modulus for periods of depressurisation or the dynamic (initial tangent) modulus for vacuum pressures encountered under surge conditions,[17] with $\nu=0{\cdot}48$ for PE subject to biaxial stressing.[18,19] A safety factor of 1·5 against the collapse (critical) pressure given by equation (2) being obtained is considered sufficient[16] given the well defined geometry encountered when lining pressure pipe.

The procedure described above is essentially that implemented in the Rolldown Technical Manual[16] for design against liner collapse, which is a good example of industrial practice based on the latest fundamental research.

A major programme of research has been undertaken[11,20,21] to verify the proposed design procedure in the presence of gap imperfection only. Extensive physical testing of cured-in-place pipe linings under elastic (short-term) loading[20,21] conditions and subject to a range of gap configurations has been undertaken. The results so obtained have been compared with those obtained using complementary mathematical techniques incorporating the results of wide-ranging materials testing, and excellent correlation has been obtained.[11,21]

## Buckling capacities of cured-in-place pipe linings for gravity pipes

Cured-in-place pipe (CIPP) is an installation technique by means of which a polymeric pipe lining is directly cast against the wall of a deteriorating host pipe.[2–4] A thermosetting resin is impregnated at ambient temperature into a flexible (polymeric needle felt) tube with a cross-sectional perimeter equal to the inner circumference of the host pipe; the tube is then pressure inverted against the wall of the host pipe from a suitable access point, and heated *in situ* (using water, steam or air) to cure the resin, thus forming a structurally competent lining. CIPP installation is rapid and straightforward and is not affected by water ingress or small gaps and voids in the host pipe; the technique is therefore particularly well suited for the rehabilitation of gravity sewer pipes. After curing, the lateral connections can be remade with ease.

Extensive test measurements using a particular commercial lining procedure[5,21,22] demonstrate that for this type of lining, a small and approximately evenly distributed gap (see the section 'Imperfection study' above) in the range 0·25–0·4% radius forms between the lining and host pipe as a result of curing shrinkage. In addition, the rehabilitated system will (or must be assumed to be) subject to quadrant ovalling, normally in the range 2–10% of the nominal host pipe internal diameter.[1,4] Thus, in this case, equations (3) and (4) reduce to

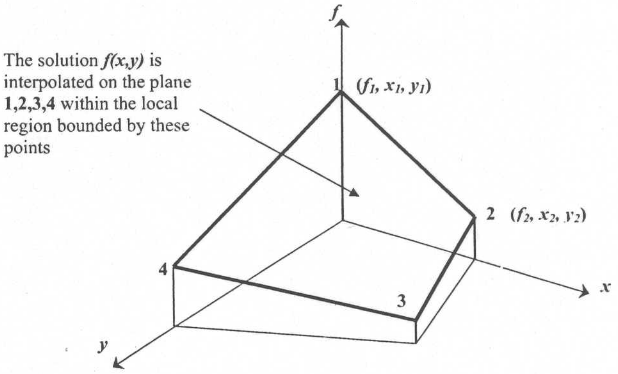
$$\log\left(\frac{p_{\text{crit}}}{E'}\right)=f\left[\log\left(\frac{D}{t}\right),\ \frac{\text{symm. gap}}{R},\ \text{quad. ovality}\right] \qquad (6)$$

For practical systems, the design parameters will normally be in the range

$$D/t=30-100;\ \text{system ovality}=2-10\%;$$

$$\text{characteristic gap}=0{\cdot}25-1{\cdot}0\%$$

Again it should be recalled that the ovality to be taken in any particular situation is purely a function of the *system* geometry immediately before lining, and can be either assumed or based on specific measurements (e.g. obtained from a CCTV survey[2,3] of the pipe). A sensible minimum value to use (i.e. for uncracked pipe) is 2% based on typical manufacturing tolerances. The gap, which is a *characteristic* of the particular CIPP installation technique being used, can be accurately obtained from the results of laboratory tests,[21] or approximately from measurements taken on typical installations. In either case, it should be borne in mind that the overall characteristic imperfection associated with a particular installation technique will contain contributions from thickness and modulus variations, and will inevitably be somewhat greater than the measured mean gap. A safety factor of 2 is traditionally associated with this application.[1,4]



**6 Interpolation of a function *f(x,y)* as a generalised bilinear function of its parameters *x,y***

Within the required parameter range, equation (6) is not imperfection-sensitive, and arguably the most convenient way of obtaining a general solution to this four-dimensional relationship is to interpolate through standard results obtained by any convenient mathematical procedure. Accordingly, finite element results for critical values of $p_{\text{crit}}/E'$ ($\nu=0{\cdot}35$) have been obtained at

$$D/t=30,\ 50,\ 75,\ 100;\ \text{quadrant ovality}=2,\ 5,\ 10\%;$$

$$\text{symmetrical gap}=0,\ 0{\cdot}25,\ 0{\cdot}5,\ 0{\cdot}75,\ 1{\cdot}0\%$$

Solutions for $p_{\text{crit}}/E'$ have been obtained at all these standard parameter values permutated against each other, and intermediate values are obtained by linear interpolation through adjacent standard values. The procedure can either design the lining thickness required for a new application or check the pressure capacity of an existing installation, and has been programmed in Visual Basic as a standard Windows 2000® application. The mathematical basis of the methodology can be summarised as follows:

Normally, a value must be obtained for $D/t$ necessary to sustain a specified safety factor $F$ against a working pressure $p_0$ causing buckling at a given total imperfection. Under these circumstances, and in the presence of a single imperfection (e.g. gap), the solution to equation (3) can be approximated in a local region spanned by four known solutions (Fig. 6) as

$$f(x,y)=a_0+a_1x+a_2y+a_3xy \qquad (7)$$

where $x$=gap, $y=\log(p_{\text{crit}}/E')$, $f=\log(D/t)$ and $p_{\text{crit}}=Fp_0$.

Equation (7) expresses $\log(D/t)$ as a bilinear function of $\log(p_{\text{crit}}/E')$ and gap. Thus, knowing the solutions $f_i(x_i,y_i)$, $i=1,4$ as delineated in Fig. 6 yields four equations to solve for the interpolation parameters $a_i$ in equation (7). This can then yield the value of $\log(D/t)$ corresponding to any $\log(p_{\text{crit}}/E')$, gap within the interpolation zone 1,2,3,4. Alternatively, if it is required to obtain the critical pressure for a lining of given $D$, $t$, gap then put $y=\log(D/t)$, $f=\log(p_{\text{crit}}/E')$ in equation (7) and proceed as before.

In the presence of both gap and ovality, the simple geometric representation of Fig. 6 is lost, nevertheless equation (7) can be re-expressed in four-dimensional form as

$$f(x,y,z)=a_0+a_1x+a_2y+a_3z+a_4xy+a_5yz$$
$$+a_6zx+a_7xyz \qquad (8)$$

where $x$=gap, $y$=ovality, $z=\log(p_{\mathrm{crit}}/E')$, $f=\log(D/t)$ and the design problem posed by equation (8) is in essence solved in the same way as equation (7).

The proposed procedure assumes two-lobe buckling behaviour as illustrated in Fig. 1*b*, since both imperfections are essentially symmetrical, and extensive physical testing of representative systems[5,12] has always yielded two lobe failures in good agreement with the anticipated mathematically obtained collapse pressures. In this respect, it is pertinent to note that the only situations which can lead to two lobe deformation deteriorating to one lobe behaviour are the absence of either friction or a dominant imperfection,[23] and neither of these conditions are obtained in practice. Numerical experiment has shown that the presence of even 1% friction leads to stable two lobe behaviour in the presence of a dominantly symmetrical imperfection, while the absence of a dominant imperfection will inevitably lead to random behaviour. If a particular technique cannot be argued to yield a two lobe critical pressure, a good approximation to the equivalent single lobe value can be obtained by factoring the result so obtained using equation (2) and Table 1.

Short-term and creep testing in the as cast condition of CIPP systems having both gap and ovality imperfections is currently under way[5] and the results so obtained are being correlated with those from independent mathematical modelling[12] in order to provide verification of the proposed design methodology for cured-in-place linings.

## Conclusions

- Buckling is the dominant mode of failure for cylindrical thin-walled linings subject to collapse pressures, and is a strong function of both the nominal geometry and the structural imperfections in the system.
- The different types of imperfection that can be obtained in a lined pipe have been deduced, and their physical origins identified. In particular, the total imperfection in any given system has been shown to be comprised of independent components categorised as follows:
  (i) A *system* imperfection in the pipe being lined.
  (ii) A *characteristic* imperfection which is a function of the lining installation procedure.
- On this basis, a suitable generalised design procedure has been identified for cylindrical polymeric linings under conditions of both short and long term collapse pressure loading.
- To demonstrate the generalised approach, applications to both gravity and pressure pipes and involving two significantly different lining materials and procedures have been considered, and a major programme of research into the structural behaviour of polymeric pipe linings is under way to verify the proposed procedures.

## Acknowledgements

The author gratefully acknowledges the financial and technical support for the work reported here from the Engineering and Physical Sciences Research Council (UK), Insituform Technologies, and Severn Trent Water. Based on a presentation at the Plastics Pipes XII conference held in Baveno, Italy in April 2004.

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