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STRUCTURAL REHABILITATION OF EGG-SHAPED BRICK SEWERS

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ABSTRACT: The WRc's *Sewer Rehabilitation Manual* (SRM) design formulas are reviewed and discussed. Also reviewed is the limited test data available. Several apparent inconsistencies in the WRc information are noted and alternative methods suggested.

This paper makes clear the need for updated design methods for Type I liners for the structural rehabilitation of egg-shaped brick sewers.

1. INTRODUCTION

The known failure modes of egg-shaped brick sewers and their causes are discussed in a paper published by Serpente (1994) and the WRc's *Sewerage Rehabilitation Manual* (SRM) (WRc, 2001). This information is related to properties of brick sewers and their pipe-soil interactions. In general, all buried structures rely on support from the surrounding soil to support their loads. This is even more the case for egg shaped brick sewers that have essentially zero vertical load capacity as a free standing structure. Thus, the first priority of the rehabilitation designer must be to assure that adequate soil support is in place or can be accomplished by appropriate external grouting (Underwood and Rees, 1985, 1983).

Further, Underwood and Rees (1983, 1985) point out that the load capacity of brick strctures is more dependent on the strength of the jointing material than on the brick itself; and that the structural performance is ''dependent upon being maintained in a constant and uniform state of compression by the surrounding ground ''. Thus, the top circular portion of a brick egg sewer acts as an arch in compression with the lower portion acting as the footings for the arch. This requires that the soil support resists horizontal movement at the base of the arch and allows the sidewalls to develop the required reaction forces. This assumes, of course, that the shape and fabric of the brick egg is near enough to ideal to be functioning as designed. There is little that rehabilitation systems can do to correct the shape of a deteriorated brick sewer and indeed rehabilitation of such structures should not be attempted if deformation exceeds 10%.

In the early 1980's the Water Research Centre (WRc) of Swindon, England performed extensive research and testing (WRc, 1982, 1983) to support design of rehabilitation systems for both pipe and brick sewers. The resulting design methods were codified in 1984 (Forth Edition 2001) and published in the very comprehensive *Sewerage Rehabilitation Manual* (SRM) (WRc, 2001). While other design references exist for circular pipe, e.g., ASTM F 1216, the SRM is the only source for rehabilitation design in brick egg sewers in widespread use (especially so in the USA). The SRM is in widespread use in the UK and is the basis for many country-wide standards.

6. WRc DESIGN (For both Circular & Egg sewers)

The WRc SRM defines three types of rehabilitation systems based on the bonding of the annulus grout to the liner material:

> Type I – Grout bonds to both liner and sewer wall producing a composite structure. Calculate bending moment at crown and design liner to take all tensile load and sewer wall all compressive load; other than space taken by annulus grout, grout is ignored.
>
> Type II – Grout bonds to sewer wall but not to liner. Assumes that the liner acts as a flexible pipe supported by grout/sewer wall/soil whose design limit state is hydrostatic pressure due to ground water in the annulus between the grout and the liner. Liner design for egg sewers assumes the critical section is the lower side wall that is treated as a straight beam anchored at the ends subjected to linearly increasing hydrostatic pressure from invert to springline. Design calculations are based on deflection and flexural stress limits. No calculation involving soil loads is required, but Type II liners are considered "structural"!
>
> Type III – Liner is permanent form-work for grout. Any structural enhancement must be attributed to grout but no design method offered.

7. TYPE I DESIGN – WRc

Figure 1 gives the physical model on which Type I design is based,

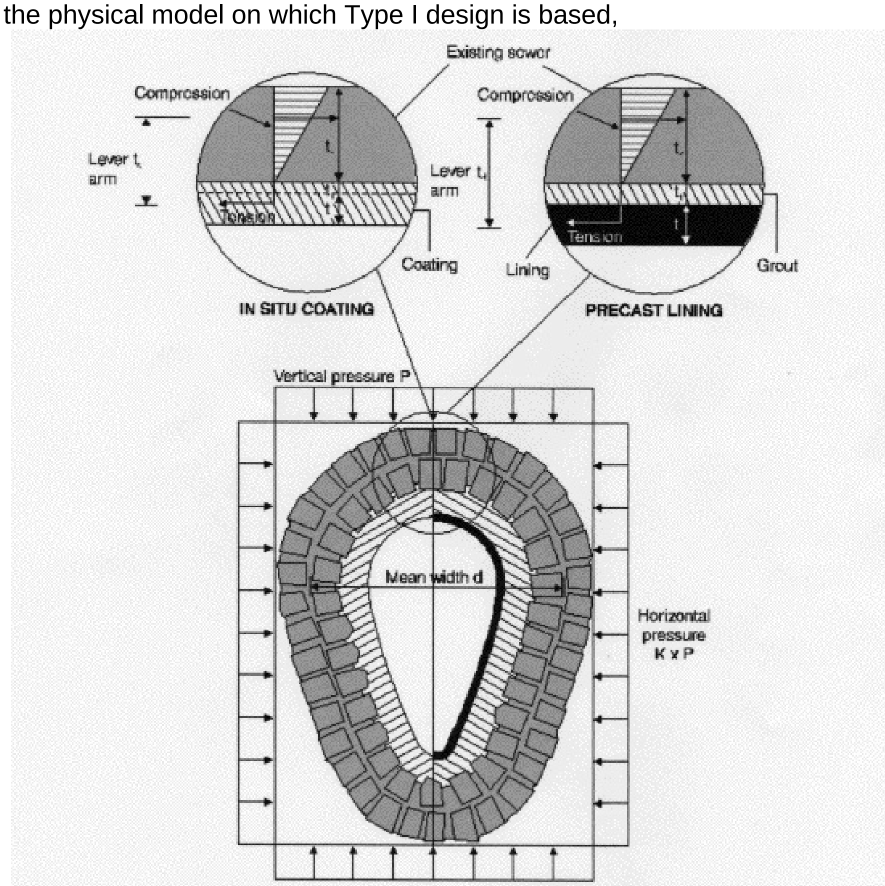

Figure 1. Model for Type I design for brick egg sewer (WRc SRM Figure 4.11)

Figure 2 is a spreadsheet design showing the calculations required by Type I design. The design approach assumes uniform vertical pressure (P) and uniform horizontal pressure (KP, K<1.0) producing a pure bending moment (M) that, in turn produces pure compression in the brick and pure tension in the lining. This implies that the neutral axis is at the interface of the brick and grout. Formulas are given for calculating both the values of the moment and the length of the lever arm (distance between the force vectors). Given these values, the magnitude of the tension force is determined and compared with the maximum allowable tension in the liner. A factor of safety (FoS) of 2.0 is recommended. The maximum allowable tensile stress in the liner is limited to a value of $0.267w_S/t$ (w_S = width of lining at the springings, and t = lining thickness) to take account of the limited shear strength of the grout bond to the lining. As far as this author can determine (attempts to obtain source documents failed), this is an empirical formula based on experimental data, the details of which are unavailable at this writing (WRc/Glennie, 1982).

The design example calculation of Figure 2 is from a field test of several renovation liners performed in 1982 (WRc, 1983) for which there are field data and Finite Element Analysis (FEA) data to compare to design calculations. The Type 1 liner was a 12 mm thick high-stiffness glass reinforced plastic. The annulus grout was a typical (for 1982) low strength (7 N/mm^2) cementitious material. The design for circular sewers is the same as for egg shape except the moment constant C = 0.5 for K = 0 and C = 0.3 for K = 0.4.

<u>WRc Design Sheet for Type I Egg Shaped Pipe Linings</u>

Notes: 1. Type I requires that grout bonds to both the lining and the host pipe.
2. Insert values for P,K,d,t2, and t1; program calculates design results.

PARAMETERS

1	Vertical pressure on sewer, P (psi) §	P	0.133	N/mm^2
2	Select ratio K, =0 for voids left in soil support, =0.4 otherwise*	K	0.4	
3	Crown bending moment coefficient C, =.17 for K=.4, C =.61 for K=0	C	0.17	
4	Mean width of existing sewer, d	d	700	mm
5	Wall thickness of existing sewer, t_2	t_2	100	mm
6	Estimated minimum annulus, t_1	t_1	5	mm
7	Lining material thickness, t	t	12	mm
8	Long term tensile strength	s	55.2	N/mm^2
	(Limited to 0.267 w_S /t; w_S = width of lining at the springline)*	s_{max}	12.9	N/mm^2

CALCULATIONS

1	Lever arm, $t_d = 0.67\ t_2 + t_1 + 0.5t$	t_d	75.0	mm
2	Crown bending moment, M=CPd^2/4	M	2775	N-mm/mm
3	Lining tensile force, $F = M/\ t_d$	F	37.0	N/mm
4	Lining tensile capacity, $T = st < s_{max}\ t$	T	154.3	N/mm
5	Factor of safety, FoS =T/F >2.0	T/F	4.17	

* Limited by shear strength of grout bond to liner as established by WRc tests.

Figure 2. Sample calculation for Type I liner

While the simplicity of this design method is appealing, it suffers several questionable attributes. There may be a serious error in the stated value of the moment constant C for egg-shape sewers. The values of C for circular sewers appear to be too high by a factor of 2. Watkins and Anderson (1999, p. 416) give the value of the moment at the crown $M = (1\text{-}K)Pd^2/16$, for K = 0 gives C = 0.25 and for K = 0.4 gives C = 0.15, 50% of the values given in the SRM. Although the SRM states that the values of C for circular sewers are calculated from formulas from Roark (Young 1989, p. 270), this author's application of the Roark formulas confirm those values of C given by Watkins and Anderson. The values given in the SRM for egg-shaped sewers are derived from FEA studies and "frame analysis" and, therefore, may not be related to the same error in statement as the circular case. However, without access to these source documents, no critical analysis is possible short of doing independent FEA studies. This point will be discussed further in Section 5 Test Data.

Other concerns with this simplified design method include: 1) ignores thrust generated by the assumed load, 2) over simplifies strain/stress distribution, 3) confuses flexural & tension stresses, and 4) ignores fundamental engineering requirements of grout properties in a composite material. The first three of these will be considered in Section 4 Type I Design – Engineering Mechanics of Composite Material. The forth area concerns the fact that the role of the grout is seriously under valued in the WRc design method. In this method the grout enters the calculations only by its thickness contributing to the moment (lever) arm and the limitation on liner tensile stress due to the likely bond strength of the grout to the liner.

The effectiveness of a composite material (brick, grout, and liner), even assuming perfect bonding, depends on the strain compatibilty of the component materials. Assuming the liner to be a GRP (glass reinforce polymer/plastic), all three components are considered to be strain limited. However, their specific strain limits differ by a factor of about 50; 1.0% for GRP and 0.02% for grout and brick. As the only physical mechanism for transferring loads to the liner is by strains in the grout, this transfer is limited by the strain limits of the grout. To determine this strain limit effect on the limiting performance of the liner we must turn to a more detailed engineering mechanics analysis of the composite structure.

4. **TYPE I DESIGN -** ENGINEERING MECHANICS OF COMPOSITE MATERIAL

First, it must be acknowledged that the following analysis, like the WRc's of the previous section, makes the illogical assumption that the load (moment) is applied after the renovation liner is installed. While this can be accomplished in controlled test situations, it certainly is not the case in the practical application of renovation liners in deteriorated sewers. Certainly, the latter case should be the focus of developing realistic design guidance for the installation of renovation systems. This topic has been explored in other papers (McAlpine 2001, 2003). However, the focus of this paper is the critical review of the WRc design standard and possible alternatives to that standard. So let's get on with it.

Figure 3 gives a simplified schematic of the three component composite material under study. The appropriate engineering mechanics analysis is that of the Transform – Section method that transforms the component materials into a single material with equivalent flexural mechanical properties. The transformation is accomplished using the ratios of modulii of the various materials. The transformed section can then be used to determine the neutral axis and the section's moment of inertia that are required to determine stress distribution (as well as strain). Again, the example calculation uses the renovation system used in Figure 2 for the WRc calculations. The modulus values used are derived from the WRc Report NO: ER 107E (WRc 1983).

The neutral axis of the transformed all-grout section falls well within the area representing the brick and the moment of inertia of the transformed section Ic = 75,000 N/mm^2 (Young 1989,p.117). Thus, the flexural stress due to the moment M = 2775 N-mm/mm may be calculated as $\sigma = M\,(y - y_{na})\,/\,Ic$. At the interface between the grout and the liner y = (12 – 54.8) and σ = - 1.583 N/mm^2 which yields a strain of

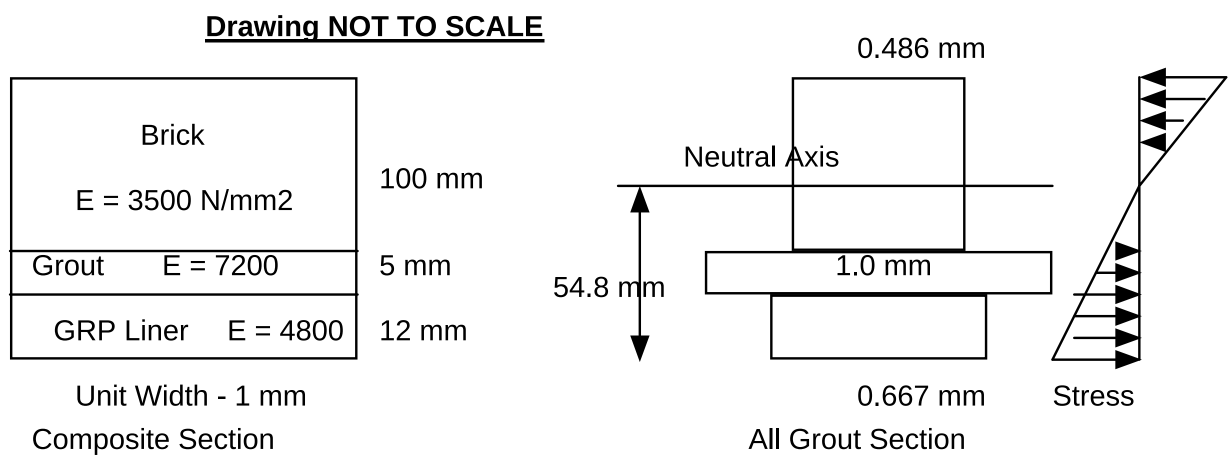

Figure 3. Transformed section of Brick/Grout/GRP liner Composite

220 microstrains, about the maximum allowable grout strain. In the same manner, the stress at the outer surface of the liner is calculated as – 2.03 (4800/7200) = – 1.33 N/mm^2. If we take this as the maximum allowable flexural stress in the 12 mm liner, the maximum allowable tensile force is 12 x 1.33 = 16 N, not the 154 N calculated in the WRc method of Figure 2 based on maximum shear bond strength. Further, it should be noted for use in the next section that the calculated strain in the outer surface of the liner at the crown (where strain gages were located in field tests) is 282 microstrains (using E = 4800).

One might reasonably argue that when the grout fails it simply cracks and allows additional strain in the liner as the crack widens, This assumes the grout remains bonded to the liner and the brick. It is this author's experience with D-load and soil cell testing of annulus grouted liners in concrete pipes that this assumption is not valid. Once the grout forms a radial crack, the grout then cracks circumferentially at a location within the grout thickness determined by the specifics of the liner and grout. This effectively separates the liner from the sewer wall and destroys the composite action (McAlpine 1994).

5. TEST DATA

The WRc conducted field test in an out of service 900x600 mm brick egg sewer of nine (9) different renovation methods (including no action as baseline) (WRc 1983). Three (3) of the liners were Type I, one was type II, two were Type III and three were not classified by WRc definition (original sewer, repointed/replcement of lost mortar and CIPP without grout). Surface loads were increased and strains and deflections at crown and springline were recorded. All ungrouted test sections failed at approximately the same load as the original sewer section. All grouted sections showed a significant increase in load bearing capacity over the original structure (2x to 4x). The magnitude of structural enhancement appeared more a function of the volume of grout (grout thickness) in the annulus than the type of liner under test. For example, the two Type III liners (2mm and 3 mm thick) produced approximately the same increase in load capacity as the thicker (10 mm, 40 mm and 12 mm) Type I liners. An additional indication of the dominant importance of the grouting to structural enhancement in brick egg sewers is the comparison of the grouted vesus un grouted CIPP tests results. The grouted CIPP (12 mm) produced a load capacity of 3x the un grouted CIPP. (Amazingly, the WRc report discounts the grout contribution and uses the the test data to validate its design method. Justification: low cement content and sewer environment .) Underwood and Rees (1983, 1985) also comment on this disparity.

This WRc report presents comparison of test data, design calculation and a finite element analysis and concludes that there is sufficient agreement to validate the design method – hardly the case! As shown in Table 1, 2 and 3 the correlation with alternate designs suggested in this paper is much better than with the WRc SRM method of Figure 2. The two columns headed by Design Method x 0.5 assume that the moment calculation for the egg-shape is too high by the same factor (2) as for the circular case. Clearly, this need not be the case. Indeed it is quite possible that the moment coefficient C = 0.17 for egg-shape is correct. Of course if this is the case, the design calculation result is even further from the measured strain or the FEA result. The ratio of WRc calculated strains to FEA computed strains are 2.24, 2.98, and 2.98 for test sections 5, 6, and 9 – all Type I liners. Similar ratios of calculated to field test data are 1.34, 2.44, and 3.9. Clearly, these results do not support the validity of the WRc design method.

Table 1. Crown Strain (μs) for surface load of 333 KN/m^2 for test section 9 (12 mm GRP)

Source of Data	WRc SRM	WRc SRM x 0.5	Transform Section	Transform Section x 0.5
Field Test	160	160	160	160
FEA Study	210	210	210	210
Design Calculation	625	312	282	141

Table 2. Crown Strain (μs) for surface load of 333 KN/m^2 for test section 6 (40 mm PRC)

Source of Data	WRc SRM	WRc SRM x 0.5	Transform Section	Transform Section x 0.5
Field Test	55	55	55	55
FEA Study	45	45	45	45
Design Calculation	134	67	88	44

Table 3. Crown Strain (μs) for surface load of 333 KN/m^2 for test section 5 (10 mm GRC)

Source of Data	WRc SRM	WRc SRM x 0.5	Transform Section	Transform Section x 0.5
Field Test	350	350	350	350
FEA Study	210	210	210	210
Design Calculation	470	235	245	122

8. CONCLUSIONS

This paper has shown that the WRc rehabilitation design for Type I liners has serious theoretical and practical flaws. Although this paper focuses on the brick egg sewer problem the design method is applicable to circular sewers and for this case it appears that the WRc formula for crown bending moment is in error by a factor of two. Data from an extensive set of field tests and FEA computations provide poor correlation to the design method calculated strains in the liner. The field tests clearly implies major structural benefit related to the annulus grout, with only weak relation to the liners under test. Yet the WRc design method marginalizes this grout effect. Further, this design method places an upper limit on long term flexural strength to a formulated value based on bond strength of the grout to the liner (formula determined by testing). This upper limit is much higher than the strain limit of any cementitious grout. The validity of this design method is questionable.

An alternative design method, transform section analysis of composite materials (beams), produced calculated values of strain in the example liner much closer to the experimental and FEA results than the WRc method. This alternative method is based on a accurate physical model and a rigorous engineering mechanics analysis. It is no more complicated to use than the WRc method and it does not make any of the simplifying assumption used in the WRc method.

Further work is required to validate the value given by WRc for the moment coefficient C = 0.17 (K = 0.4) for egg sewers. The apparent discrepancy in the moment coefficients for the circular case must be resolved.

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