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Structural Rehabilitation of Semi Elliptical Concrete Sewers

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Abstract

This paper discusses the design for structural rehabilitation of man-entry size cast-in-place semi elliptical concrete sewers. Many such sewers were built in the early 1900's and are still in service, notably in Chicago, Los Angeles and Seattle. Even though some were lined with clay tiles even these are now in need of repair due to severe hydrogen sulfide induced corrosion above normal flow lines of these concrete structures. As these structures were design as arches, the principal load is compression in the wall section and no reinforcing steel is required. The inverts of these sewers are most always very flat (very large radius of curvature).

This paper discusses design approaches that address the repair of the plain concrete structure to restore (or increase) its wall section properties, i.e., load capacity. The rehabilitation materials considered are strain compatible with and bond to the concrete structure walls. Thus, composite material design is appropriate using classical transform-section analysis. Also discussed is the often-overlooked (ignored) process of determining the current state of stress of the structure before rehabilitation. This consideration is shown to be important in rehabilitation design and points out the need to accurately determine (as possible and practical) the actual total load on the structure. A design example from a past project is given.

Introduction

Cast-in-place concrete/masonry arches have been used as load bearing structures for thousands of years. Semi elliptical arches of both plain and reinforced concrete have been used as sewer structures for at least the last 100 years in the USA, most notably in Chicago and Los Angeles (see Figure1). While this author has not conducted a historical search of the design literature, it appears that the semi elliptical shape was chosen as an approximation of a parabolic arch. If one assumes that the vertical soil load is uniform over the span of the arch then the pressure line (equilibrium polygon) of the load is parabolic and the moments in the arch will be minimized (the parabola is the funicular curve for this load distribution) (Structural Engineering Handbook,

1990) and (Timoshenko and Gere, 1961). Of course, the horizontal soil pressure will reduce the moments produced by the vertical load.

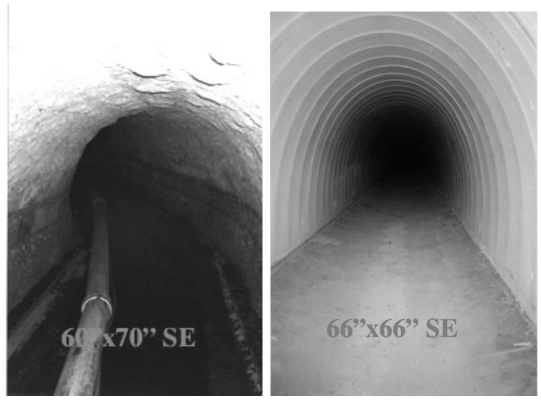

Figure 1. Semi Elliptical Sewers in Los Angeles.

Figure 2 graphically illustrates these arch shapes as well as that of a semi circular arch, the funicular curve for uniform radial pressure. As the area between the center line of the arch and the appropriate funicular curve is proportional to the magnitude of the moment at that location in the arch wall (Timoshenko & Gere, 1961), the determination of the actual nature of the soil load may be important in the design/analysis of the wall stresses.

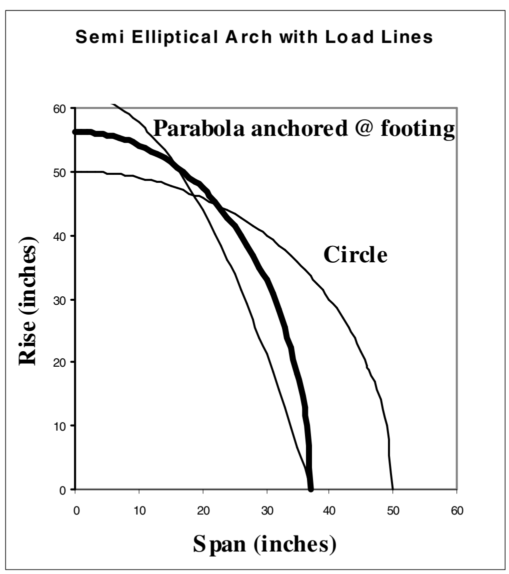

Figure 2. Semi elliptical arch and two funicular load curves.

Design Assumptions

Due to the uncertainty of the exact shape of the load influence line relative to the shape of the semi elliptical sewer, we will assume that the worst case failure state to be flexural cracking due to moments at the crown. Further, we will assume that this moment $M = KPR^2$ where R = radius of curvature of the centerline of the pipe wall at the crown. The original design radius will be designated R_0 and its associated wall thickness will be designated T_0. Likewise, the radius and wall thickness of the deteriorated wall will be defined as R_1 and T_1 and those dimensions after rehabilitation as R_2 and T_2. For convenience, let $k = T_1 / T_0$ and $C = T_2 / T_1$. Thus k is a measure of the extent of wall deterioration (k<1) and C is a measure of wall thickness restoration (C>1) from the rehabilitation process. To illustrate the design method we shall consider an example semi elliptical sewer in Los Angeles with R_0 = 46 inches and T_0 = 7.5 inches.

Design Method

The design method to be discussed requires that the rehabilitation materials employed form and function as a composite material with the plain concrete of the semi elliptical sewer being rehabilitated. That is, it must be adequately bonded to the old concrete so that future strains in the old concrete are effectively transferred to the rehabilitation material AND the two (or more) materials are strain compatible. For example, a high flexural strength material perfectly bonded to the old concrete will be ineffective if it cannot develop high stress within the strain limit of the concrete. The basic material property requirement is that the materials have similar elastic modulii.

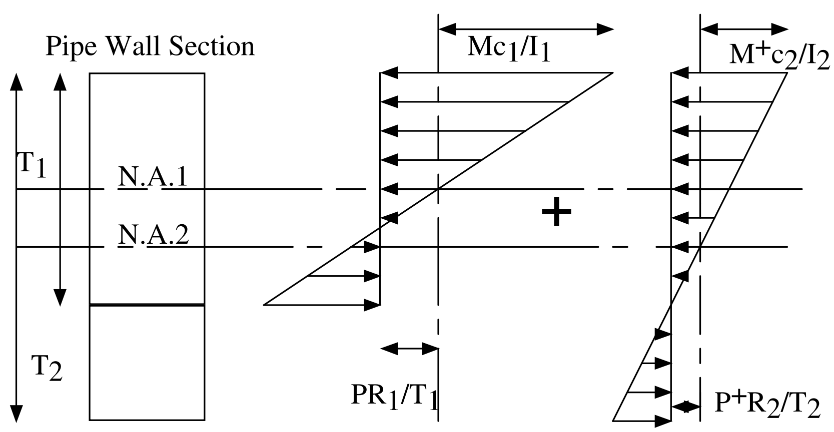

Figure 3. General wall stress in deteriorated wall (T_1) and rehabilitated wall (T_2).

The total tensile stress on the inside surface of the original wall at the crown is determined by (using $c = T_0 / 2$, $I = T_0^3 / 12$ and K' = 6K)

$$\sigma_0 = Mc/I - P R_0/T_0 = 6M/T_0^2 - P(R_0/T_0) = 6KP(R_0/T_0)^2 - P(R_0/T_0)$$
$$= P(R_0/T_0)(K'(R_0/T_0) - 1) \qquad (1)$$

Normal design practice would require $\sigma_0 < 0.5$ MOR = 0.5 (7.5) $(fc')^{0.5}$ then MOR = 474 psi and $\sigma_0 \leq 237$ psi for fc'= 4,000 psi.

As the sewer ages and the wall thickness is reduced by H2S gas corrosion process the wall thickness just prior to rehabilitation is $T_1 = k T_0$, $k \leq 1.0$ and $R_1 = R_0 + 0.5 T_0 (1 - k)$. The expression for stress at the deteriorated inner surface of the wall is

$$\sigma_1 = P(R_1/T_1)(K'(R_1/T_1) - 1) = P[R_0 + 0.5 T_0 (1 - k)/k T_0][K'(R_0 + 0.5 T_0 (1 - k)/k T_0] - 1] \qquad (2)$$

This stress equation is plotted for several values of k and P for $(R_0/T_0) = (46/7.5) = 6.13$ in Figure 4.

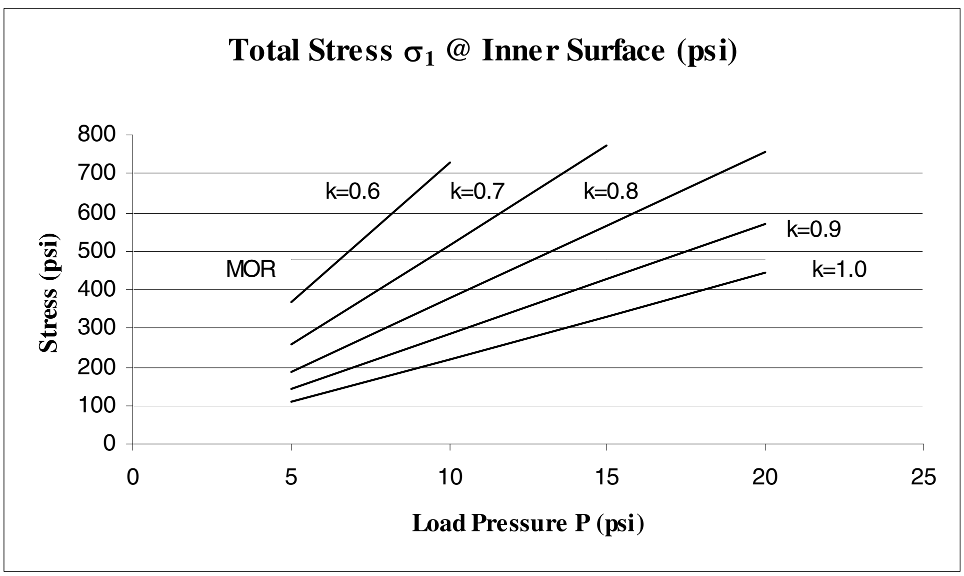

Figure 4. Stress levels for R_0 = 46", T_0 = 7.5" and K' = 0.75.

Figure 4 indicates the original wall thickness produced a flexural cracking safety factor of 2.0 at about P = 10 psi and that the wall should crack at k = 0.75 at this load. We now assume that the current state of deterioration is k = 0.8, a loss of 1.5 inches from the original wall thickness. The calculated value of stress at the deteriorated surface σ_1 = 377 psi that is within 100 psi of the cracking stress. The rehabilitation strategy is to add wall thickness to the deteriorated surface to reduce the sensitivity of the section to future loads (moments) and thus increase the in-service safety factor. It must be noted that the rehabilitation process cannot affect the stress/strain existing at the time of rehabilitation unless the load changes after rehabilitation. Of course, the worst case (and most reasonable) is to assume increased future loads. Further, it is reasonable to assume that the critical stress remains at the deteriorated surface and the rehabilitation objective is to maximize the in-service safety factor within the constraints of cost and loss of conduit capacity.

The transform-section method (Ugural & Fenster, 1987) is required for stress analysis of composite materials. This method transforms the two (or more) materials that are characterized by their respective elastic modulii E1 (original wall material) and E2 (rehabilitation material) into a homogeneous structure of one of the materials. To transform the rehabilitation materials into original wall material the thickness of the rehabilitation material is multiplied by the modular ratio n = E1 / E2. For cementitious materials $E = 33\ \mu^{1.5}\ fc'^{0.5}$ where μ = density (PCF) and fc' = 28-day compressive strength. Reasonable values for these parameters are 145 PCF and 4,000 psi for the original concrete and 120 PCF and 6,000 psi for the rehabilitation material resulting in n = 1.08. Thus it is reasonable to assume n = 1.0 for high strength cementitious rehabilitation material. It should be noted that n is approximately 0.1 for most plastic rehabilitation material and 0.5 for GRP.

For high strength cementitious rehabilitation materials (n = 1) the addition of wall thickness will reduce the stress resulting from future loads P^+ and the resulting moments M^+. Because the critical stress is at the deteriorated surface equation (1) must be amended as follows

$$\sigma_2 = \sigma_1 + \sigma_1^+ = \sigma_1 + M^+ y / I - P^+ R_2 / T_2 = \sigma_1 + 12\, M^+\, y / T_2^3 - P^+ R_2 / T_2 \qquad (3)$$

where $M^+ = K\, P^+\, R_2^2$ and y = distance from N.A. 2 and surface $T_1 = T_1 - T_2 / 2$. Defining $C = T_2 / T_1$ yields $y = (2 - C)\, T_1 / 2$ and equation (3) becomes

$$\sigma_2 = \sigma_1 + \sigma_1^+ = \sigma_1 + 6\, K\, P^+\, R_2^2\, (2 - C)\, T_1 / (C\, T_1)^3 - P^+\, R_2 / T_2 \qquad (4)$$

Note that if $T_2 = 2\, T_1$, i.e., C = 2 then the future bending stress at the deteriorated surface will be zero because this surface is at the neutral axis for the rehabilitated wall section. In this case, the critical stress would be at the new wall surface at a distance of T_1 from the neutral axis and all tensile bending stresses due to future moments would be located in the newly added materials. Also, future stresses in the existing wall material would be entirely compressive thus reducing the existing tensile stresses from past loads. This may be a feasible design strategy for smaller values of k, say k ≤ 0.5. However, if the structure has not collapsed with this range of k-values then the original design was either very conservative (safety factor >> 2.0) or the soil has formed and arch over the structure and the true load on the sewer is much less than assumed in the original design (or both).

Following the procedure used in developing equation (2), using $T_2 = C\, T_1 = C\, k\, T_0$, $R_2 = R_1 - 0.5\, (T_2 - T_1) = R_0 + 0.5\, T_0\, (1 - k) - 0.5\, (C\, k\, T_0 - k\, T_0) = R_0 + 0.5\, T_0\, (1 - Ck)$ and K' = 6 K,

$$\sigma_2 = \sigma_1 + \{P^+ [(R_0 + 0.5\ T_0 (1 - C\ k)) / C\ k\ T_0]\} \{[K' (R_0 + 0.5\ T_0 (1 - C\ k)) (2 - C) / C^2\ k\ T_0] - 1\} \quad (5)$$

Equation (5) is plotted in Figure 5 for k = 0.8 and several values of C. Figure 6 shows the rapidly decreasing value of increasing values of C by plotting the factor (C – 2) / C^3 that represents the reduction in stress sensitivity to future bending moments.

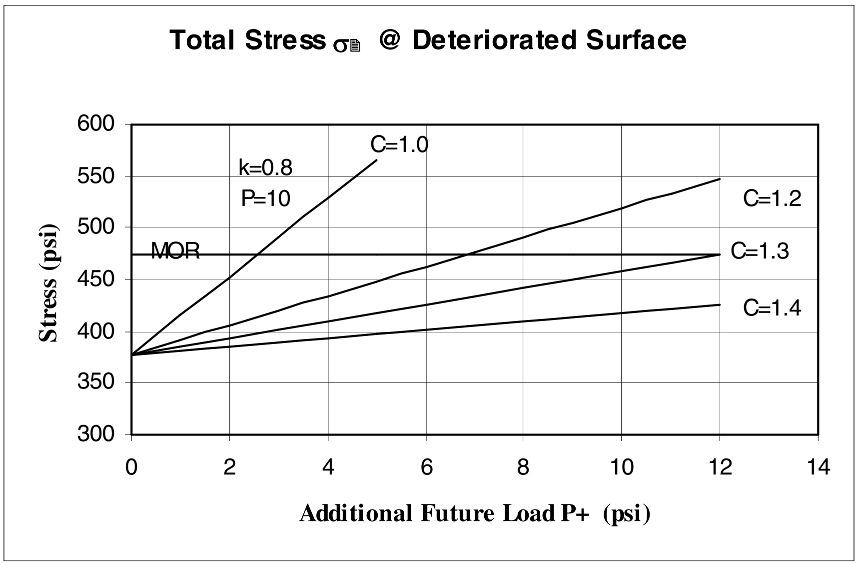

Figure 5. Improving section properties by cementitious rehabilitation material.

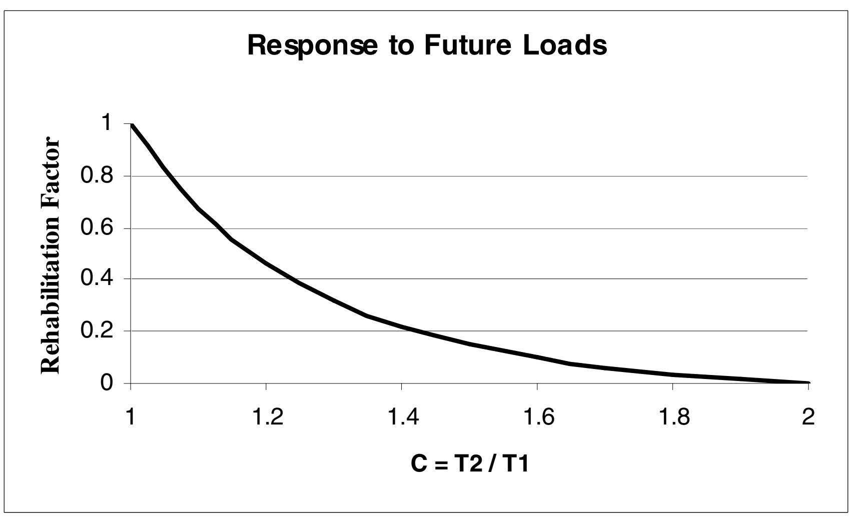

Figure 6. Rehabilitation factor (2-C) / C^3.

Table 1 gives the approximate in-service safety factors derived from Figure 5 for the various levels of rehabilitation (values of C).

Table 1. Safety factors before (C = 1.0) and after rehabilitation for k = 0.8.

C = T2 / T1	Safety Factor
1.0	1.25
1.2	1.70
1.3	2.20
1.4	3.40

Conclusions

Rehabilitation methods that effectively form a composite structure with the existing wall material can significantly improve the in-service safety factor of deteriorated plain concrete semi elliptical sewers. This is also true for other shapes as the above analysis deals only with wall section properties. The essential requirements for composite action are that the rehabilitation material adequately bonds to the deteriorated surface and is strain compatible with the host material. In rehabilitation situations the deteriorated surface is quite uneven (rough) and mechanical bonding is adequate to insure that future strains in the host structure wall are transferred to the rehabilitation material. Both field and laboratory tests have confirmed this (Ahmad & McAlpine, 1994), (WRc, 1983). The strain compatibility requirement simply recognizes that the ability of the host material to transfer loads to the rehabilitation material is limited by its remaining strain capacity.

References

Ahmad, S. and McAlpine, G. (1994) "Structural Characteristics of the Danby Pipe Renovation System", *Proceedings, Third Materials Engineering Conference, Materials Engineering Division/ASCE, INFRASTRUCTURE: New Materials and Methods of Repair*, November 13-16, 1994, San Diego, Calif.

Structural Engineering Handbook (1990), Third edition, edited by Edwin H. Gaylord, Jr. and Charles N. Gaylord, McGraw-Hill, 1990, pp. 17-1 – 17-3.

Timoshenko, S. and Gere, J.M. (1961) *Theory of Elastic Stability*, McGraw-Hill, 2nd Edition, 1961, pp. 290-292.

Ugural, A.C. and Fenster, S.K. (1987) *Advanced Strength and Applied Elasticity, Second SI Edition*, Elsevier Science Publishing Co., 1987, Section 5.9.

WRc. (1983) *Structural Tests on a Renovated Brickwork Sewer at St. Helens, Merseyside*, Report No.: ER 107E, WRc Engineering, Swindon (UK), June, 1983.