Failure of prestressed concrete pipe at Regina, Saskatchewan

by

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Dr Jacob Feld (Consulting Engineer, New York), wrote that open discussion of failures, with presentation of all pertinent observations and physical data, was a professional duty, more so than the description of glorious successes. Much more could be learned, as a warning of the limitations for safe use of material combinations, from a Paper like the Author's, than from volumes of detailed reports on structures that showed no distress. Of course, closer scrutiny of many structures might uncover some worthwhile information.

37. In his recent professional work, Dr Feld had been required to inspect and diagnose the cause of several structural failures. Difficulties with similar reinforcing wire, similarly installed on a vertical concrete cylinder, were the subject of one such investigation. Actually, the difficulties were brought to sharp attention by the collapse of a 2.5-million-gallon sludge-holding tank, at 5.45 a.m. on April 21, 1961, when 1.6 million gallons came out as a surge wave and overturned three railroad cars.

38. The public authority concerned agreed that the information collected to explain the cause of failure was sufficiently valuable to warrant public disclosure. Summary articles on the general heading 'Corrosion wrecked prestressed tank', followed by numerous discussions appeared in *Engineering News-Record* from the issue of 2 November, 1961 until Dr Feld's reply on 25 January, 1962. A summary of the findings would be of interest, since the same type of wire failure occurred in the absence of the proximate causes listed by Mr Legget.

39. Located at two separate disposal plants, the tanks were set in batteries of eight in two lines, spaced somewhat apart, with closure walls around a large operating room. The outsides of the tanks were covered, for architectural reasons as well as for heat insulation, by a brick cladding laid with 2-in. cavity. The inside dimensions of the tank were 103 ft dia. by 35 ft high in one plant, and 118 ft by 32 ft in the other. Failure at 10-year age occurred in a section of the tank exposed to the north-east, the direction of maximum driving rain. Some difficulty was being experienced with roof drainage leaking into the cavity wall. The coping was not prestressed although built as a vertical continuation of the tank barrel, and relative contraction between barrel and coping cracked the contact at roof level and fractured the waterproofing.

40. None of the concrete nor the gunite contained any calcium chloride or any other addition to the mix. The collapse exposed the condition of the reinforcing in that section. Later demolition of the remainder of the tank permitted close inspection of the reinforcement and comparison of conditions in the portions exposed to the temperature changes; rain leakage and possibly salt air moisture had penetrated the brick cladding and the gunite covering the wires, as against the interior exposure of controlled fairly uniform temperature and humidity. The operating equipment and metal conduits in the room showed no undue rusting or corrosion.

41. Before the collapse of the tank, there were several warnings over the years that the wires were being altered by corrosion, when the gunite covering, within the room

areas, cracked and spalled. The cause in some instances was found to be complete disintegration of the aluminium connectors used to splice the ends of the wires as run off the spools. Other areas were close to pipe sleeves penetrating the tank walls, while others were not explainable from such causes. The wires found to be rusted and pitted were cleaned and red-leaded.

42. Careful surveys of possible electrolysis were made with negative result; no stray electric currents could be detected.

43. After the failure and demolition, it was clearly shown that:

- (a) The concrete was sound and dense, the sludge liquid had not penetrated even 1/16 inch.
- (b) All embedded normal reinforcing steel was sound, with normal rusting on the surface and no loss in area.
- (c) The vertical post-tensioned steel wires, 0.160-in. diameter, located in grooves in the 12-in. wall thickness, on the inner face and later filled with mortar to give a ¼-in. protection from the sludge, were in perfect clean and smooth condition.
- (d) Galvanized metal slotted anchors set in the outer gunite covering for holding the brickwork were considerably eaten away by corrosion and rust. In some points, the back of the slot had been in contact with the outermost horizontal hoop wires.
- (e) The horizontal hoop wires, stressed by pulling a 0.160-in. wire through a die to a 0.140 in. dimension, were severely corroded, more so on the outer area, with practically no aluminium connectors found intact and with many wires severely reduced in area or completely parted. Only a few wires, not over 10% in the interior wall area were found clean and smooth. Some of these, when bent, were found to have internal longitudinal streaks of rust and a tendency to split with shiny surfaces. No clean conditions were found in the wire which fell away from the collapsed portion, but here a complete examination was not possible since the rubble was considerably mixed up.

44. Exposure of some wires in tanks which did not fail also showed longitudinal splitting of the wire as well as serious rust conditions. All of the remaining tanks were at present being provided with welded steel plate liners designed to take the full lateral pressures.

45. Corrosion and erosion of the wires caused sufficient loss in area to permit failure, purely from static liquid pressure. The proximate cause, discounting the added loss in strength from the disintegration of the connectors, electrolytic travel of metal at contact of dissimilar metals, oxidation from vapour exposure and from seepage through the wall covering, was considered to be the phenomenon loosely called stress corrosion. The wires had been re-heated during the stressing, without subsequent annealing. The curvature was formed by a sharp change in direction of pull causing large differential stress in the parallel fibres. It seemed quite likely that the disturbance of the interlocking surfaces of the atomic structure (these contacts were called Fermi surfaces in solid physics) opened ultramicroscopic discontinuities which permitted electrolytic metal transfer and explained the longitudinal splitting. Once the wire was split, corrosion set in; no environment except a perfect vacuum would be perfect protection.

46. Much could be learned from these costly and sometimes unfortunately hazardous incidents. Each taught a lesson of what not to do. Several such examples were contributed by Dr Feld as discussions to the 4th International Prestressed Concrete Congress, Rome, 1962 and the elaboration of detail on this incident would appear in its Proceedings.

Dr N. Stutterheim (Vice-President, South African Council for Scientific and Industrial Research) wrote that the Author was to be congratulated for the clear and concise summary of the circumstances surrounding the failure of pipe-sections, as produced for the

City of Regina during 1952. The paper was of particular significance and importance to civil engineers and concrete technologists, as well as to all authorities concerned with the use of large diameter prestressed-concrete pipes. It was unfortunate that, as a result of the protracted litigation which made the technical evidence relevant to the case *sub judice*, this important information was only made available, first by Monfore & Verbeck⁹ and now by the Author, many years after the event.

48. It is clear from the record that the technical evidence to the effect that calcium chloride played the key rôle in the corrosion of the reinforcement, was so strong that it was accepted by both litigants as well as by the various Courts. However, from the Author's paper it was clear that it could not be concluded that calcium chloride, even in relatively large concentrations, caused corrosion of all steel exposed to a cement matrix in which this chemical was present. The Author stated specifically that the longitudinal prestressing wires were not subject to corrosion, and that in the case of the circumferential wires, the outside surfaces (those away from the core) were still bright, in marked contrast to the inside surfaces of the same strands.

49. These statements were significant if one wanted to learn one important lesson from this failure. It was Dr Stutterheim's considered opinion that, although the presence of soluble chlorides in concrete predisposes the steel to corrosion, there were physical and chemical conditions in the concrete or in the cement paste surrounding the steel which also had a material influence. For instance, if the concrete or mortar surrounding the steel was of high quality (low water cement ratio, low permeability), the presence of calcium chloride would not necessarily lead to corrosion of steel, and certainly not in the short time found at Regina. On the other hand, corrosion would take place rapidly if the cement paste at the surface of the steel was fairly permeable, or was not bonded to the steel surface, and the elements required for corrosion to proceed at some speed, viz. moisture, calcium chloride and oxygen, were available.

50. It was therefore not without significance that the corrosion was found to have occurred in the region of contact between the steel and the core. Since the wire was wrapped onto a hardened concrete core, and subsequently covered with the external protective coating, it was inevitable that the sprayed protective mortar would not always have covered the steel around its whole circumference. The contact area between core and wrapped wire, being under high pressure, could not be penetrated by cement particles; only cementitious material in liquid phase could reach this area. In these regions therefore, there would still be unbonded steel surfaces, and the physical and chemical requirements for inhibiting corrosion of the steel would not exist.¹⁰ The aqueous solution present in the fresh cement paste, containing also chloride, would be drawn into those areas by capillary forces, and so bring about rapid corrosion.

51. Corrosion on the inner surfaces of circumferentially-wrapped prestressing steel on a hardened concrete core had been observed by Dr Stutterheim, even in cases where no calcium chloride was added to the concrete or mortar, though the process was then relatively slow. If calcium chloride were present, it would be logical to conclude that the risk would be very much enhanced; the Author's observations on the Regina pipe bear this out.

52. The conclusions to be drawn from this aspect of the Regina pipe failure therefore appeared to be:

- (a) The use of calcium chloride in all concentrations should be prohibited in circumferentially-wrapped prestressed concrete pipes, tanks, and structures of a similar nature.
- (b) The whole process of wrapping steel on hardened concrete with subsequent covering by a protective layer, requires intensive study, with a view to eliminating the risk of corrosion, even if no corrosion-promoting electrolytes like calcium chloride are added, because such electrolytes could subsequently penetrate to the steel from the atmosphere (sea air), ground, or the liquids in the container.

Mr S. McConnel (Retired civil engineer) wrote that in view of developments in prestressed concrete pipe lines on the Continent, it seemed strange that technical knowledge still took so long to cross the Atlantic. Over 50 years ago reinforced-concrete pipes with a steel interlining were used in Belgium and in one case at Norwich. In 1917 about 250 miles of centrifugally-cast pipes were employed in an irrigation scheme in Southern Italy, while French engineers started prestressing concrete pipes about 30 years ago. Since that date a considerable number of successful schemes had been carried out. Unlike the American ones these dispensed with a steel interlining. Attention was drawn to the construction of a 150-mile pipe line near Mombasa, Kenya, in which a reinforced-concrete core with embedded prestressed longitudinal wires was centrifugally cast, wound with prestressed wire and then protected by an external coat of mortar applied mechanically.

54. The work was carried out to a considerable extent by African labour, without any serious difficulty and last year while in Mombasa the writer was informed that maintenance had been practically negligible. In this case as at Regina, steel pipes were ruled out of court owing to the impossibility of obtaining steel. To proceed with the construction of a pipe line where the percentage of rejected individual pipes was as high as 31% seemed to be, to express it mildly, most unusual. It was well known that calcium chloride caused corrosion in steel and the use of a water heavily dosed with sulphates should also have been regarded with misgiving. The publication of this Paper would, however, in no way lessen the confidence of many engineers in the efficacy of prestressed non-cylinder pipes which have already proved so successful outside the American continent.

Dr C. E. Bird (National Building Research Institute, South Africa) wrote that the Author was to be congratulated on his most balanced summary of a complex and involved problem. The failure of prestressed-concrete pipes at Regina and the subsequent litigation had focused the attention of corrosion and concrete technologists on the various problems concerning the construction of sound prestressed concrete pipes in which the steel is not subject to corrosion. The following comments might be of interest.

56. It has been fairly well established that corrosion of reinforcing is enhanced by:

- (a) Oxygen differential cells,
- (b) variation in salt concentration, and
- (c) differences in the pH of the material surrounding the steel.

(a) Oxygen differential cells

57. Recent tests by the National Building Research Institute had shown that reinforcing steel surfaces in contact with salt-free fresh concrete, i.e. uncarbonated concrete, were subject to rapid anodic polarization. Thus, owing to variation in cover thickness and permeability of the concrete, no differential aeration cells could operate. With the uniform addition of 2 per cent sodium chloride by weight of the cement, however, the anodic polarization curve became much less steep and steel surfaces to which oxygen diffusion was restricted became permanently anodic. This may have accounted for the preferential attack on the inner surfaces of circumferentially-wrapped prestressing steel in the Regina pipes; the outer surfaces having been nearer the pipe surface probably received cathodic protection.

(b) Salt concentration

58. When 2 per cent sodium chloride by weight of the cement was added in an attempt to obtain a uniform salt concentration, it was found that this condition was in fact not achieved; the concentration was highest near the casting surface, probably due to transportation of the salt by water moving to the surface where evaporation took place.

59. If this phenomenon occurred in the Regina pipes the salt content at the outer surface of the core would have been higher than at other points in the pipe. The

portions of the spirally-wrapped wires in contact with the core would then have been in contact with a higher concentration of calcium chloride than those portions against the outer layer of cover concrete. This variation in salt content on the inner and outer areas of the prestressing wires may have contributed to the rapid deterioration of the portions of the wires in contact with the core. Moreover, the addition of calcium chloride reduces the overall electrolytic resistance of the concrete resulting in increased corrosion currents.

(c) *Variation in pH.*

60. The surface skin of concrete carbonates on exposure, especially at elevated temperatures. This reduces the pH near the surface. The reaction is soon stifled, however, owing to the sealing effect of the formation within pores of the more voluminous carbonation product, CaCO_3 . Although no information was available to substantiate this, it was possible that the circumferential wires may have been in contact with a carbonated core surface on the inside and with an uncarbonated concrete with a high pH on their outer surfaces. This differential pH condition could also have contributed to the attack on the inner surfaces. This type of corrosion could take place even in the absence of salt although at a much reduced rate.

61. It was extremely difficult, at this stage, to ascertain what relative effects the factors mentioned above might have had on the failure of the Regina pipes. A consideration of these factors may, however, assist concrete technologists in appreciating the importance of the various factors involved in the corrosion of prestressed reinforcing.

The Author, in reply, wrote that the contributions of Dr Feld, Dr Stutterheim and Dr Bird were greatly appreciated. They added much useful information not only with respect to the various phenomena that were associated with the Regina failure, but also in relation to more general features of corrosion in prestressed concrete structures.

FIG. 1: PORTION OF FAILED PIPE

63. The opinions of Dr Stutterheim and Dr Bird as to possible causes of the corrosion of the wire agreed so closely with those of the Author and his colleagues that it remained only to say that further examinations of specimens of failed pipe made since the Paper was written had confirmed the invariable existence of corrosion of the circumferential wires where in contact with the core, and not on the side covered by the shell. Some 'splitting' of wires was also observed.

64. If only for the record, a photograph (Fig. 1) was submitted of a portion of one of the pipes which failed badly, following removal of a part of the shell. The irregularity of the surface of the core on to which the circumferential wire was wrapped was clearly evident.

65. The Author greatly regretted if any statement in his Paper was such as to give any grounds for Mr McConnel's suggestion that 'technical knowledge still took so long to cross the Atlantic', presumably from east to west, unless the reference was meant to apply to the delay in the submission of the paper, due to legal restrictions as explained in the text. Correspondingly, the Author could find nothing in what he had written to give any warrant to Mr McConnel's further implication, in his closing words, that prestressed concrete pipe had proved to be generally unsatisfactory in North America. The failure at Regina was, fortunately, unique in North American practice. It had been described with constructive intent only so that engineers on both sides of the Atlantic could benefit from the study that had been made of the unusual failure, with possible ultimate benefit to the advance of prestressed concrete pipe design and construction in general.

REFERENCES

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