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Experimental investigation of buckling collapse of encased liners subjected to external water pressure

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ABSTRACT

This report presents the experimental results of a comprehensive investigation on the buckling of an encased liner under external water pressure. The pre- and post-buckling behaviours of tightly and loosely fitted liners, as well as their collapse mechanism, were investigated by performing a series of experiments using novel pressurizing equipment. The experimental results clearly show that an encased liner can collapse due to inelastic single-lobe buckling or elastic buckling, depending on the liner and constraint conditions. In addition, the existing related solutions are discussed, and it is identified that none of the solutions can appropriately evaluate the critical pressure for both tightly and loosely fitted liners. Moreover, recent buckling accidents are discussed, and suggestions for safe design are presented.

1. Introduction

Thin liners are usually placed in host tunnels to improve hydraulic performance, protect primary linings, and so on. For instance, steel pipes are installed in water supply tunnels, and plastic liners are employed to rehabilitate aging sewer pipes [1–4]. The structural design of such liners is relatively simple; in most cases, it is only necessary to calculate the thickness that can resist the designed external pressure using a selected buckling equation [5–7]. However, recent buckling failures in the Newhall Tunnel [8], the Mito Tunnel [9], and a high-density polyethylene (HDPE) sewer pipe [10] clearly indicate that the hydrostatic buckling of encased liners remains a vital structural concern requiring more in-depth studies.

Regarding encased liners under external pressure, single-lobe buckling theory [11–13], as illustrated in Fig. 1, is readily considered to explain the buckling mechanism because its buckled shape assumption has been verified by numerous collapse accidents [8–10]. In addition, the buckling equations consider the conditions of both the liner and the surrounding restraints. However, the buckling mode and collapse mechanism, i.e. whether the buckling is multi-lobe or single-lobe mode and elastic or inelastic, remain topics of debate. In addition, few reports have been published on experimental studies of the buckling behaviours of encased liners, although many experimental results related to the buckling mode and critical pressure are available. Furthermore, recent buckling accidents still confuse engineers and researchers; for instance, it is not well understood why safely designed liners can experience buckling collapse or why liners buckle at various locations and not at the invert (e.g. the buckling occurred above the springline in the Newhall Tunnel, below the springline in the Mito Tunnel, and at the invert in the aforementioned sewer pipe).

To achieve more comprehensive understanding of the buckling problem, the authors conducted a series of full-scale tests using 32 encased liner specimens with various annular gaps, voids, construction faults, and filling materials. The specimens were manufactured by installing an industrial vinyl-chloride pipe inside a steel pipe and casting mortar into the space between the liner and host pipe. This report mainly presents the experimental results obtained for selected seven specimens, including three tightly fitted liners, three loosely fitted liners, and one free liner, with the objective of illustrating the buckling behaviour and collapse mechanism. The experimental results clearly illustrate the different behaviours of tightly and loosely fitted liners under external pressures. In addition, the buckling collapse mechanism is discussed in this report to enable deeper understanding of the buckling problem, as well as the effects of defects and a smooth interface. Moreover, the existing analytical solutions are discussed, and

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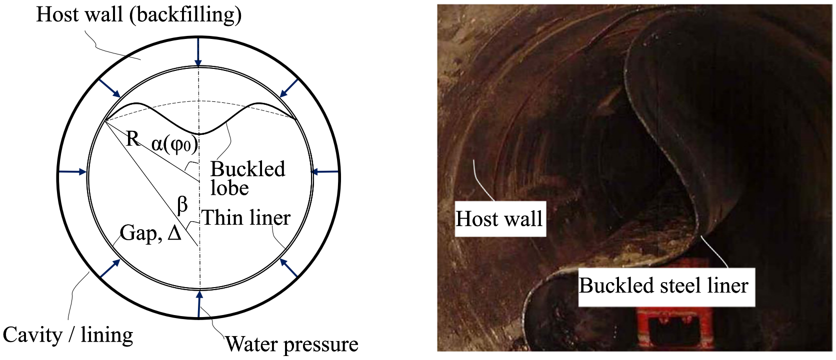

(a) (b)

Fig. 1. Buckling of an encased liner [(a) schematic profile of single-lobe buckling and (b) example of a buckled liner (D_i = 1.35 m, t = 8 mm)].

recommendations for the safe design of encased liners are provided based on the experimental results.

2. Related research and solutions

2.1. Literature review

In the past decades, many studies on the buckling of encased liners [8–25] have been performed, and some related analytical solutions have been developed based on the assumption of a smooth interface. Regarding buckling theory, the studies can be divided into two categories: those related to elastic buckling/liner instability and inelastic buckling/plastic collapse. In the inelastic buckling theory typically considered by Amstutz [11] and Jacobsen [12], the yielding of the material is used as the liner failure criterion, whereas in the elastic buckling theory adopted by Glock [13], Lo and Zhang [15], and Boot [16], the buckling critical pressure is produced by determining the eigenvalues of elastic and geometric stiffness matrices for an assumed buckling mode. However, both elastic and inelastic buckling can occur in an encased liner, depending on the liner geometry and material and its restraints. An appropriate method of designing safe encased liners is required. This requirement has been explicitly indicated in recent reports on numerical studies, e.g. those by El-Sawy [17–19] and Wang [20–22]. Using finite-element analysis, El-Sawy [17–19] investigated the buckling of tightly and loosely fitted liners and suggested regression equations for determining whether the buckling is elastic or inelastic and evaluating the critical pressure. Wang [20–22] numerically studied the buckling behaviours of circular and non-circular liners and proposed the corresponding numerical and theoretical solutions.

With respect to the experimental research, Amstutz [12] tested five steel liners tightly fitted by concrete and verified his proposed buckling equation. Aggarwal and Cooper [14] conducted a series of tests using 49 pieces of plastic liners loosely encased in a steel host pipe and reported on the experimentally obtained critical pressures and single-lobe and double-lobe buckling models. Lo and Zhang [15] also tested loosely fitted pipes and verified their buckling solution. Boot [16] conducted an experiment to investigate the elastic buckling of a liner with small imperfections and only observed double-lobe buckling. Pavlović [23] tested four free pipes with an internal support system to simulate the constraints of a host wall and reported that the bending strains were rather small compared with those of the membrane counterparts, i.e. the liners failed via elastic buckling. In addition, Gong [24] experimentally investigated buckle propagation in a pipe-in-pipe specimen with a sealed hyperbaric chamber and presented numerical analysis techniques and an empirical buckling formula. However, almost all of the aforementioned experiments only provided the critical pressure and buckling mode, whereas the liner behaviour has rarely been illustrated. In particular, analysis of the relationships between mechanical strain and displacement and acting pressure is lacking. In addition, the collapse mechanisms of encased liners under various conditions and their post-buckling behaviours have not been clarified. Furthermore, end-clamped liners have been employed in almost all past experiments, inevitably yielding critical buckling pressure overestimates [24,25]. The constraint conditions and host wall defects have rarely been considered.

Regarding practical pipe buckling, the mechanisms through which groundwater pressure builds up and is subjected to the encased liner should be clarified. In addition, to enable more comprehensive understanding of buckling, issues such as how liners behave under water pressure before and after buckling and whether elastic instability of the overall liner or plastic failure of a portion of the liner causes the collapse of an encased liner must be addressed. Therefore, the advanced experimental studies are still required [25].

2.2. Related theoretical solutions

(1) Solutions presented by Amstutz and Jacobsen

As mentioned above, Amstutz [11] and Jacobsen [12] proposed theoretical solutions to the inelastic single-lobe buckling of encased liners. The solution presented by Amstutz was the first to be widely accepted in the pipeline engineering industry, and the buckling equation proposed by Jacobsen was recommended in a technical forum due to its ability to yield conservative results readily [8]. For an encased plain liner with a mean radius R, thickness t, gap size Δ, elastic modulus E, yield strength f_y, and Poisson's ratio ν, the theoretical solution provided by Amstutz is given in Eqs. (1a) and (1b):

$$\left(\frac{12R^2}{t^2}\right)\frac{\sigma_N-\sigma_V}{\sigma_F^*-\sigma_N}\left(\frac{\sigma_N}{E^*}\right)^{3/2}=1-0.45\left(\frac{R}{t}\right)\frac{\sigma_F^*-\sigma_N}{E^*} \tag{1a}$$

and

$$P_{cr}=\left(\frac{t}{R}\right)\sigma_N\left[1-0.175\left(\frac{2R}{t}\right)\frac{\sigma_F^*-\sigma_N}{E^*}\right], \tag{1b}$$

where σ_N is the hoop (circumferential) stress in the liner, $E* = E/(1-\nu^2)$, $e = t/2$, $F = t$; $\sigma_v = -(\Delta/R)*E*$, $\mu = 1.5 - 0.5[1/(1 + 0.002E/fy)]^2$, and $\sigma*_F = \mu f_y\,(1-\nu+\nu^2)^{0.5}$. The solution proposed by Jacobsen is provided in Eqs. (2a)(2c):