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# Behavior and Analysis of Hollow Concrete Bridge Piers

## Comportement et analyse de piles de ponts creuses

## Verhalten und Berechnung von hohlen Brückenpfeiler aus Stahlbeton

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**SUMMARY**
The results of an investigation of the behavior and analysis of solid and hollow reinforced concrete bridge piers are summarized. The investigation included an experimental study of both stiffness and strength of typical piers subjected to realistic combinations of axial load and biaxial moments. Comparisons of the predictions from computer programs developed as part of the study to the results from the experimental tests showed the programs to be accurate, yet conservative predictors of stiffness, strength and behavior of solid, hollow and multicell bridge piers and bents as long as they have reasonable wall thickness.

**RÉSUMÉ**
Les résultats d'une étude du comportement et de l'analyse de piles de ponts en béton armé pleines ou creuses sont résumés. Une étude expérimentale de la rigidité et résistance de piles typiques soumises à des combinaisons réalistes de charges axiales et de moments biaxiaux est incluse. Des programmes d'ordinateur ont été développés et comparés avec les résultats expérimentaux. Les programmes permettent le calcul de la rigidité, de la résistance et du comportement de piles pleines, creuses et cellulaires de manière précise et néanmoins conservatrice tant que l'épaisseur des parois est raisonnable.

**ZUSAMMENFASSUNG**
Die Ergebnisse einer Untersuchung über das Verhalten und die Berechnung massiver und hohler Brückenpfeiler aus Stahlbeton werden dargestellt. Die Untersuchung umfasste eine experimentelle Studie der Steifigkeit und der Tragfähigkeit von typischen Brückenpfeilern, welche realistischen Kombinationen von zentrischen Lasten und zweiachsigen Momenten unterworfen waren. Computer-Programme wurden entwickelt und mit den experimentellen Ergebnissen verglichen. Die Programme erwiesen sich als genau, aber eher konservativ in bezug auf Steifigkeit, Tragfähigkeit und Verhalten von massiven, hohlen oder zellularen Brückenpfeiler, solange deren Wandstärke vernünftig ist.

## 1. RESEARCH STUDY

Recent studies [8,9] have indicated that the design of very slender compression members should be based on a second order structural analysis procedure rather than more approximate methods such as moment magnification precedures. These second order analysis procedures consider both material and geometric nonlinearities and are more efficient when implemented on digital computers. With such analysis procedures, deflection limits as well as strength limits can be included. In this study several second order analysis programs for bridge piers were developed based on a fiber model as shown in Fig. 1 [5]. The key element is a computer routine which will calculate the biaxial load-moment-curvature (P-M- $\phi$) relationship of an arbitrary section. That routine, called BIMPHI, was used as a major component of program PIER (which predicts the space behavior of a single reinforced concrete pier subjected to static loads), and of program FPIER (which predicts the space behavior of reinforced concrete frame bents of symmetrical configurations having up to two bays and three stories). The pier may be of arbitrary cross section and longitudinal configuration which is approximated by a series of stepwise uniform sections. At present, the programs can analyze a wide variety of hollow and solid cross sections with varied reinforcement parameters. The piers can have various end conditions.

In order to verify the analysis method, experimental results of several previous investigations were compared with program predictions [1]. BIMPHI was checked against several uniaxial and biaxial moment-curvature cases. Typical comparisons for biaxial moment curvature relations of an oval column are shown in Fig. 2. In the case of this biaxially loaded oval section, the agreement between experimental results and BIMPHI predictions is quite good for both strong and weak axis bending. The moments about each axis as well as the curvatures are accurately determined by BIMPHI as are the moments at failure.

Predictions from PIER were checked for both planar and space behavior of a beam-column. A typical comparison for tip deflection of a laterally loaded cantilever pier model is shown in Fig. 3. As seen in this figure, the experimentally obtained load-deflection curve and that determined by PIER are almost indistinguishable. There is excellent agreement between the load at failure.

Predictions from FPIER were checked for beam-columns and for frames such as shown in Fig. 4. The test specimens were arbitrarily selected for the study to give reasonable range and scope. As seen in Fig. 4, there is excellent agreement between the measured and predicted load-deflection behavior until major redistribution occurred. Thus, it is evident that the effective limit of FPIER is the formation of first hinging. The model does not count on deformation restraint when hinging is taking place in a frame. Again, there is good agreement between the measured and predicted load at failure.

A primary assumption used in developing program BIMPHI was that plane sections remain plane before and after bending. This assumption has been previously verified for solid sections. The possibility exists that with biaxial bending in thin-walled hollow sections, some nonplanar action might occur.

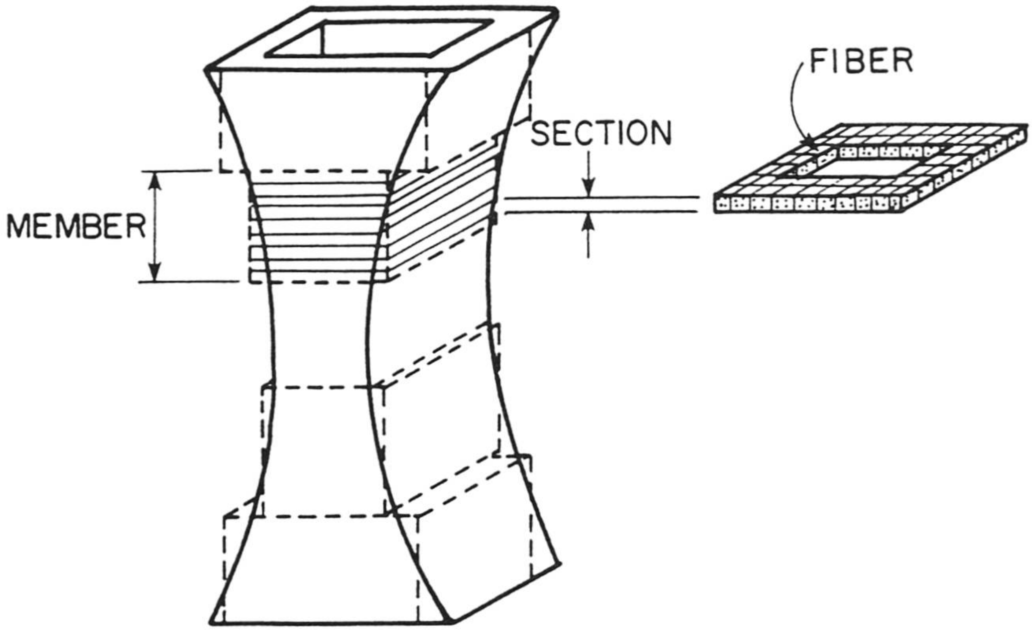


Fig. 1 Fiber model representation of a nonprismatic hollow bridge pier

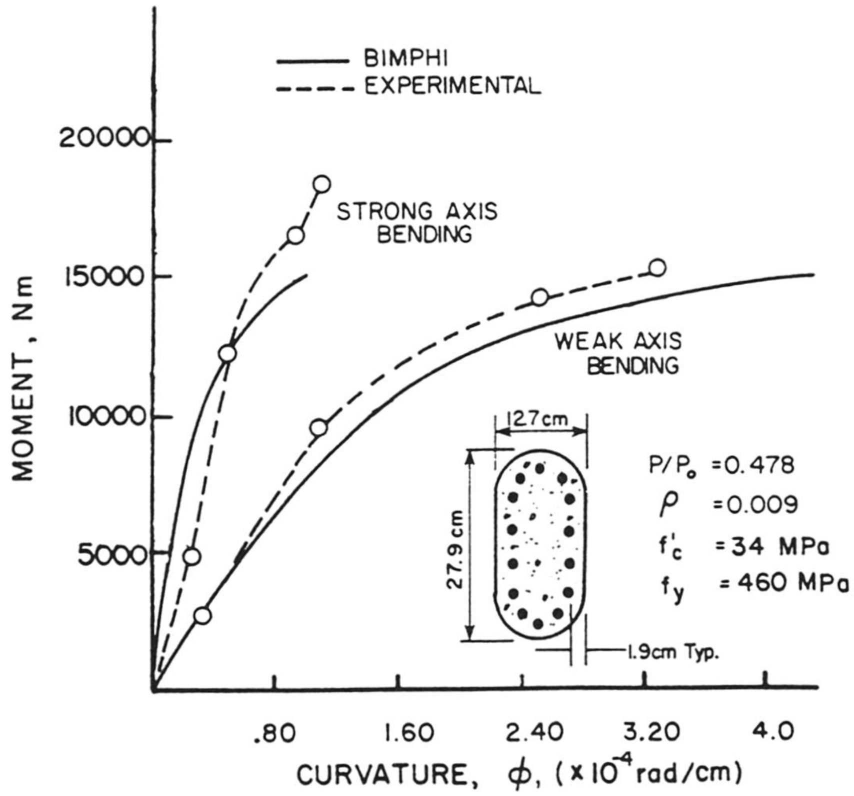


Fig. 2 Biaxial load-moment-curvature (P-M-$\phi$) relationship for solid oval section

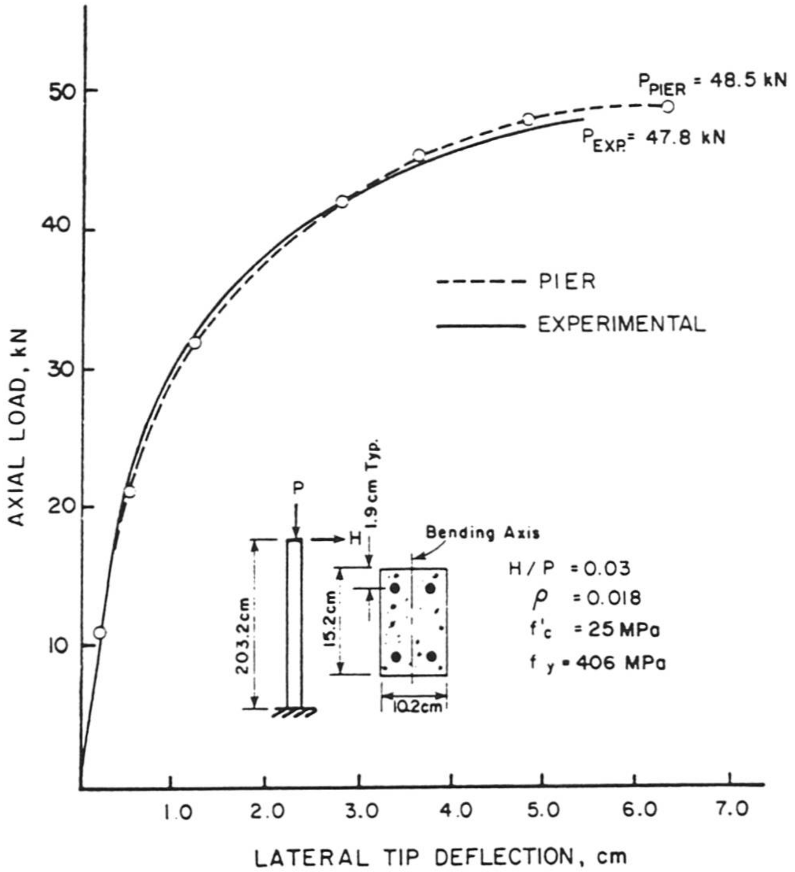


Fig. 3 Axial load versus tip deflection for laterally loaded cantilever pier model

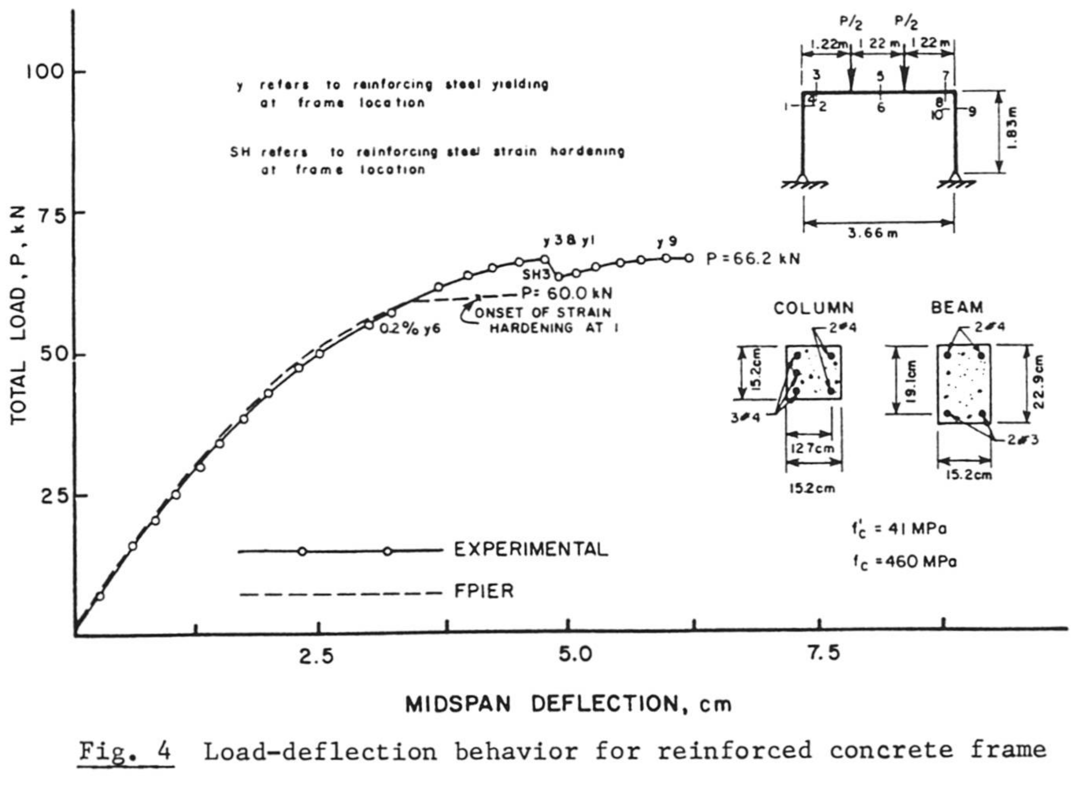


Fig. 4 Load-deflection behavior for reinforced concrete frame

Very few hollow compression member tests have been conducted. This basic assumption was examined for validity with hollow sections. Comparative experimental tests of solid, hollow, double cell and triple cell pier sections were conducted. Measured moment-curvature data from the ultimate test series of these four biaxially loaded cross sections were compared to computer predictions.For brevity, only the comparisons of results for the hollow (single cell) and triple cell sections are presented in Figs. 5 and 6. The general agreement between experimental and predicted results for the solid, double cell and as seen in Fig. 6 for the triple cell section was quite good.

At service load levels and other intermediate loading stages, the results for the single cell pier were also in good general agreement with predicted values as seen in Fig. 5. However, the ultimate loading test for that specimen indicated that near ultimate, the strain distribution deviated substantially from the assumed linear plane of strains. Only 85% of the computed ultimate moment capacity was developed. Since the major variation between test specimens was the cross-sectional shape, a series of checks was made of the possible variables. Examinations using the data from the present test series as well as the hollow test series reported by Proctor [7] and by Jobse [2] of variables such as the percentage of voids in the cross section or the wall thickness showed no trends.

However, as shown in Fig. 7, the data did indicate a significant effect of wall cross section slenderness. This was defined as shown on Fig. 7 as the ratio of unsupported cross-sectional wall length to wall thickness ($X_u/t$). Using this cross-sectional parameter ($X_u/t$), no strength reduction of any significance from the values calculated using PIER are indicated for specimens in which the wall cross section slenderness ration was 6 or less. However, in the present study for the single cell wall specimens with a wall cross section slenderness ratio of approximately 7.5, an approximate 12 to 15% decrease in capacity occurred. In Proctor's study [7], an approximate 15% decrease occurred for a thin wall specimen with a ratio of about 10. Many piers are built in the USA with these ranges [4]. Test data for even thinner wall hollow piers are very scarce, although many large piers have been built with more slender ratios. A recent report by Jobse [2] describes tests of two very slender wall hollow pier sections. Substantial reductions were found, as shown in Fig. 7.

## 2. IMPLEMENTATION

The comparisons between the physical test results and the predictions of the analytical programs establish the accuracy of programs PIER and FPIER for second order anlysis of a wide variety of solid and hollow concrete piers. Comparative design studies [4,5] of solid and cellular section tall piers for longer span bridges indicate that use of a cellular pier with the same approximate stiffness as a solid pier can result in substantial dead load reduction resulting in important foundation cost savings as well as savings in pier material costs. Use of these verified programs make it easier for designers to achieve these possible savings. In addition, the use of the programs should simplify analysis of tapered and flared piers which may be desirable for economic and aesthetic reasons.

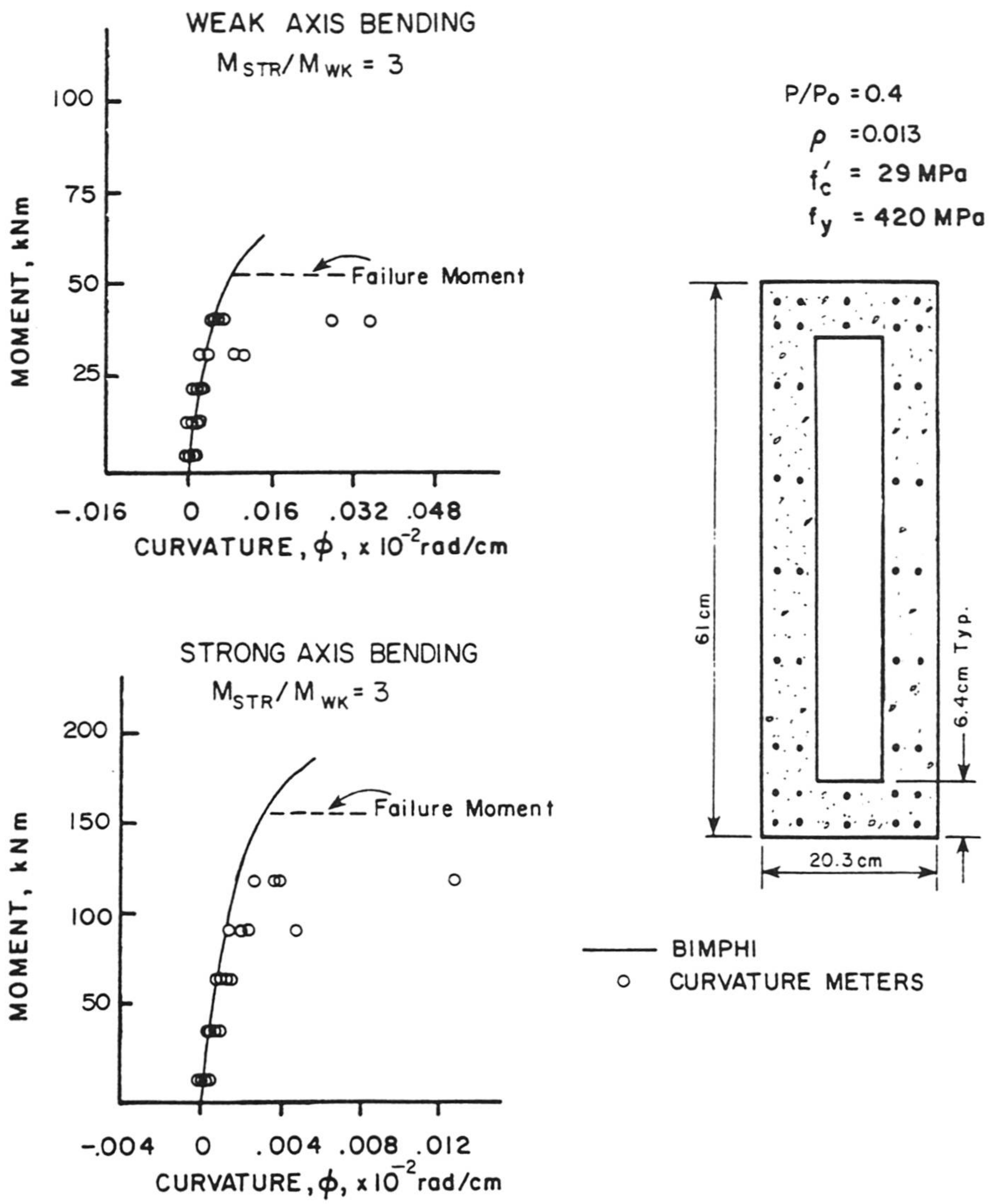


Fig. 5 P-M-$\phi$ behavior of single cell pier

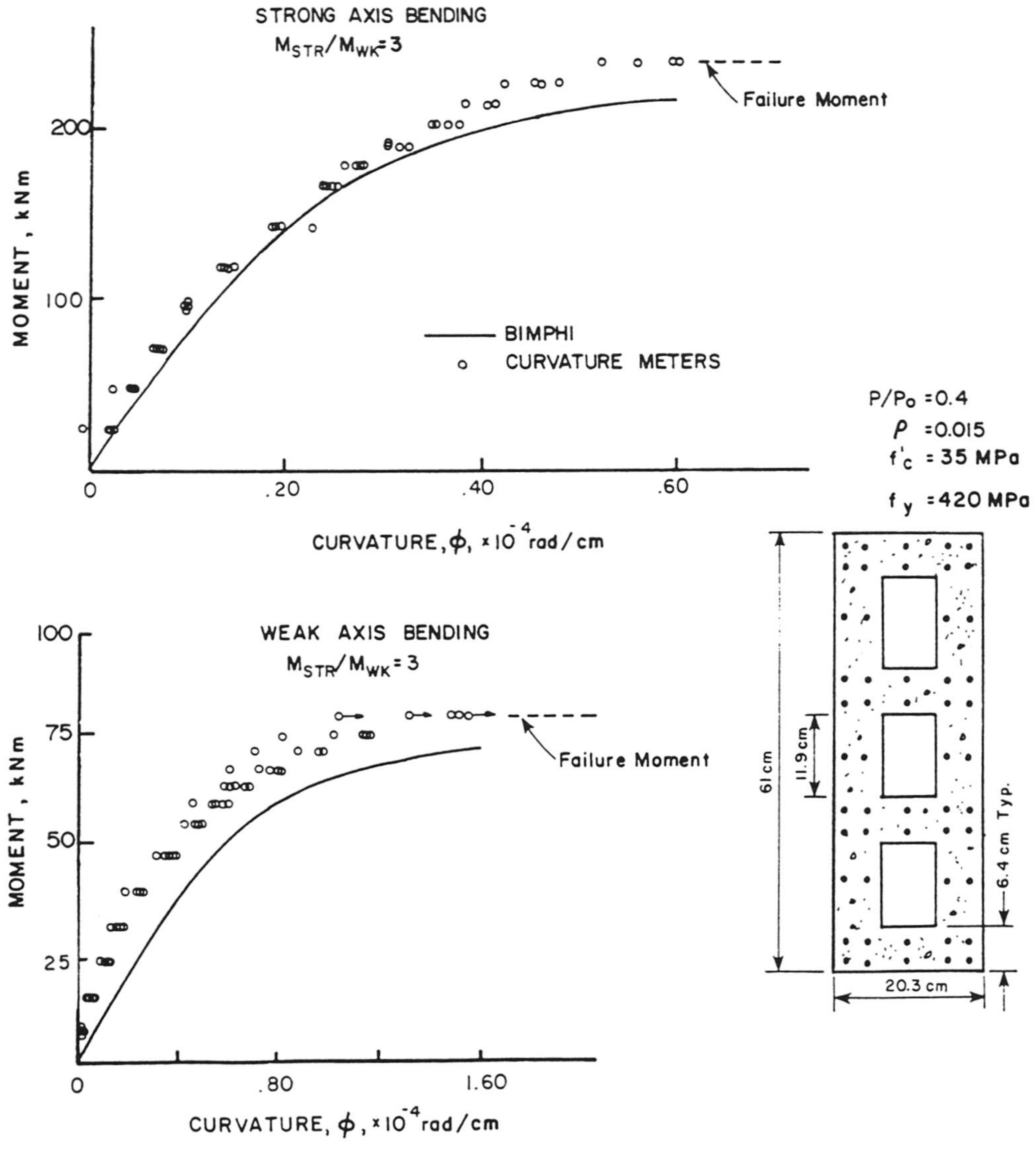


Fig. 6 P-M-ϕ behavior of three cell pier

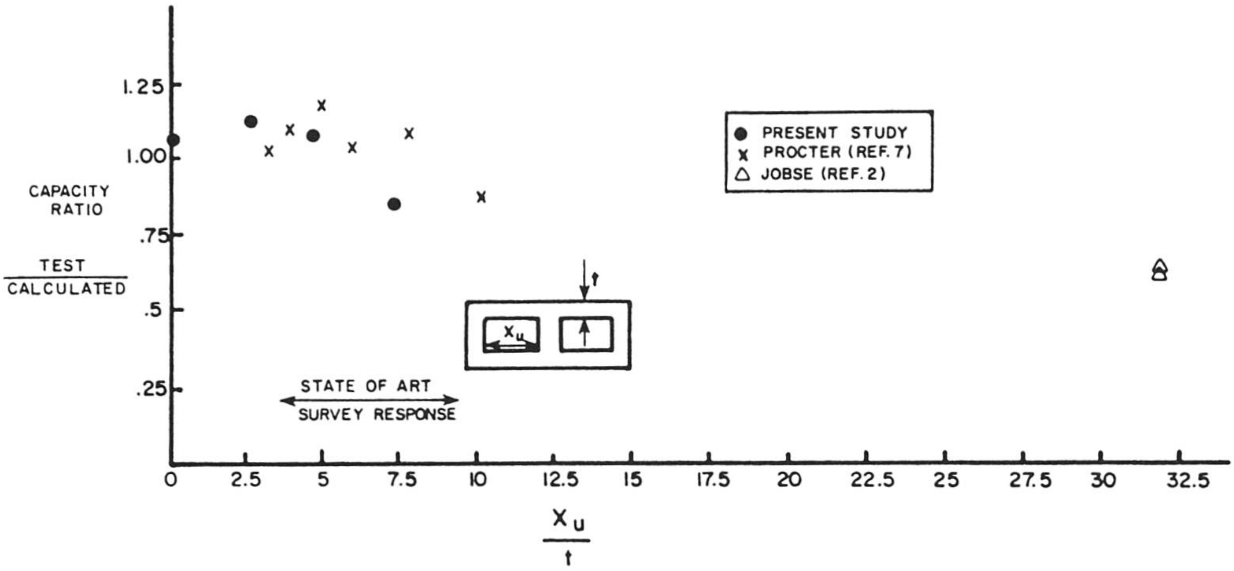


Fig. 7 Effect of wall thinness on pier capacity

## 3. CONCLUSIONS

The major conclusions from this study are restricted to primarily axial and flexural load combinations. Neither the computer programs nor the experimental test series treated significant shear or reversal forces. Futhermore, the conclusions are based on use of solid or reasonably stiff wall hollow cross sections. Limited experimental evidence raised questions as to the strength and stiffness near ultimate load of cross sections with an unsupported cross section wall length to thickness ($X_u/t$) ratio of 7.5 or greater. Further examination is required for very thin wall sections.

Within these limits, it can be concluded that:

1. Programs BIMPHI, PIER and FPIER are accurate and useful tools for the second order analysis of biaxially loaded piers.

2. BIMPHI is an accurate routine for predicting cross section stiffness for a wide range of pier shapes.

3. PIER and FPIER are accurate programs for studying single member and multiple member pier behavior which satisfy the general requirements that second order design of compression members include realistic material properties, axial load and cracking effects on stiffness, creep effects, and geometric and material nonlinearities.

4. The assumption that plane sections remain plane was verified for biaxially loaded rectangular columns of solid and cellular cross sections in all cases where the cross section unsupported wall length to wall thickness ratio ($X_u/t$) did not exceed 6.

5. Limited experimental evidence indicates that for hollow cross sections with unsupported wall length to thickness ($X_u/t$) ratios of approximately 7.5, a 15% decrease in strength occurs and there is appreciable variation of strains from planar section behavior, particularly in the tension zones of the thin wall area. Recent tests reported by Jobse [2] as shown in Fig. 7 indicated as much as 40% decrease in strength for extremely thin-wall sections ($X_u/t=32$).

## 4. NOTATION

$f'_c$ - compressive strength of concrete as measured at 28 days by 15.2 cm x 30.4 cm cylinders

$f_y$ - reinforcing steel yield stress

H - lateral load

M - moment

$M_{STR}$ - strong axis moment

$M_{WK}$ - weak axis moment

P - axial load

$P_o$ - concentric axial load strength

SH - refers to strain hardening of reinforcing steel

t - hollow section wall thickness

$X_u$ - longest dimension of hollow portion of a section

y - refers to yielding of reinforcing steel

$\phi$ - curvature

$\rho$ - ratio of reinforcing steel area to gross section concrete area

## 5. ACKNOWLEDGMENTS

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The full text of the research reports, Refs. 1 and 5, can be obtained through the National Technical Information Service, Springfield, VA 22161 U.S.A.