Precast concrete shear wall panels are used extensively in high rise construction. Their attractiveness and economy are mainly due to the high quality control that is achieved at the manufacturing plant, and the ease and speed of panel assembly at the construction site.

One of the main concerns in precast concrete construction is the method by which the panels are connected. Connections must provide adequate strength, ductility and continuity in order to insure the integrity of the structure under various loading conditions.

The typical connections currently used for elevator shaft shear wall panels...
utilize a combination of continuity bars and mechanical shear connectors. The gap between adjacent panels (required for tolerance purposes) is normally filled with a drypack concrete. To enhance the shear resistance, some fabricators have recently introduced the use of shear keys along the horizontal portion of the joint surface of the wall panel, as shown in Fig. 1. In addition, the continuity bar and mechanical shear connector system has been replaced by a post-tensioning scheme. The available design recommendations and code provisions are not directly applicable to this type of horizontal multiple shear key connection. 

RESEARCH SIGNIFICANCE

The experimental program was designed to study the various limit states behavior and the shear capacity of the multiple shear keys currently used in horizontal connections for post-tensioned elevator shaft shear wall panels. The tests results were used to develop analytical models to predict the shear capacity of the horizontal multiple shear key connection at the various limit states. The predicted values of shear capacity are compared to the measured values.

Synopsis

Seven horizontal connections typically used in precast concrete elevator shaft shear wall panels were tested to determine the behavior and capacity of the multiple shear key connection. The connections included two different multiple shear key configurations and one plain surface connection. Test results were used to develop analytical models to predict the cracking, the maximum and the ultimate shear resistances of the multiple shear key connections. The analytical models incorporated the configuration of the shear keys and the level of compressive load normal to the connection.

Fig. 1. Multiple shear key connection for elevator shaft shear wall.
Fig. 2. Overall specimen dimensions (five large keys or eight small keys within connection length for each configuration).

EXPERIMENTAL PROGRAM

Seven connections were tested, including two different multiple shear key configurations and one plain surface connection. The primary variables considered in this study were the configuration of the shear keys and the magnitude of the compressive load normal to the horizontal connection. The overall dimensions of each connection wall panel were similar to those used in the elevator shaft shear wall of a twenty-six story high rise building erected in Winnipeg, Manitoba.

Each test specimen consisted of two identical wall panels joined by a dry-pack connection. For the convenience of testing, the horizontal connection was aligned vertically in the test frame, as shown in Fig. 2. The overall length of the connection was 1020 mm (40½ in.) The panels were fabricated by Con-Force Structures Ltd., a local precast concrete company in Winnipeg. The drypack, which was compacted into the connection, consisted of two parts sand, one part normal portland cement (Type 10) and approximately 0.2 part water. The three types of connection configurations considered in the study are shown in Fig. 3.
Two levels of compressive stresses, 2 and 4 MPa (290 and 580 psi), were applied normal to the connection. These stresses represented the loads imposed on the connection due to the weight of the wall panels and the post-tensioning. This normal stress was applied using a prestressing system which was designed to prevent any constraints in the direction of the applied shear load. The pre-stress level was maintained constant throughout the tests using a pressure regulator (see Fig. 4). The joint interfaces of two multiple shear key connections were coated with a bond breaking agent in order to study the influence of a possible lack of bond between the drypack and the concrete.
Table 1. Test specimen details.

<table>
<thead>
<tr>
<th>Specimen mark*</th>
<th>Joint configuration</th>
<th>Normal stress, σ_n (MPa)</th>
<th>Compressive strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Concrete, f_c'</td>
</tr>
<tr>
<td>1NK4</td>
<td>Plain surface</td>
<td>4</td>
<td>49.1 ± 0.9</td>
</tr>
<tr>
<td>1LK2</td>
<td>Large key</td>
<td>2</td>
<td>42.6 ± 0.2</td>
</tr>
<tr>
<td>2LK4</td>
<td>Large key</td>
<td>4</td>
<td>30.4 ± 0.4</td>
</tr>
<tr>
<td>3LK4B</td>
<td>Large key</td>
<td>4</td>
<td>46.5 ± 2.6</td>
</tr>
<tr>
<td>2SK2</td>
<td>Small key</td>
<td>2</td>
<td>44.0 ± 0.2</td>
</tr>
<tr>
<td>1SK4</td>
<td>Small key</td>
<td>4</td>
<td>29.3 ± 1.0</td>
</tr>
<tr>
<td>3SK4B</td>
<td>Small key</td>
<td>4</td>
<td>49.5 ± 0.5</td>
</tr>
</tbody>
</table>

Note: 1 MPa = 145 psi.
* The first number refers to the order of testing, and the last number refers to the magnitude of preload (in MPa) normal to the connection. A letter B at the end of the identification mark indicates a specimen in which bond was artificially destroyed.

Each test specimen was loaded using a Universal testing machine to apply a monotonically increasing shear load through the centerline of the connection, as shown in Fig. 2. The two edges of the individual panels of each specimen were independently post-tensioned to avoid premature cracking in the panels. The complete test setup is shown in Fig. 4.

The shear load was applied in increments of 100 kN (22.5 kips). After each load increment, average strains in the concrete and the drypack were measured at instrumented (demic) stations located along the connection. At each demec station, strains were measured in three directions to determine the connection deformation. After the maximum load was attained, the test was continued using stroke control. Each test was terminated after the connection exhibited extensive deformation and the shear capacity was approximately constant.

The average compressive strengths of the concrete and the drypack were determined using standard 150 x 300 mm (6 x 12 in.) concrete cylinders and 75 mm (3 in.) cubes, respectively. Detailed information for all the test specimens is given in Table 1.

TEST RESULTS AND DISCUSSION

The measured concrete compressive strength ranged between 30 and 50 MPa (4350 and 7250 psi) and drypack compressive strength was approximately 27 MPa (3910 psi) for all the test specimens, as given in Table 1.

The various limit states for the connections tested were the behavior prior to cracking, the maximum load, and the ultimate shear resistance at large slip. The cracking load, V_cr, was determined as the load corresponding to the initiation of diagonal cracks in the drypack shear keys. The maximum load, V_m, was the peak load recorded during the test, and the ultimate shear resistance, V_u, was defined as the load corresponding to a slip of 5 mm (\(\frac{5}{16}\) in.) at the connection. These three limit states are illustrated on the schematic load-slip curve in Fig. 5. The measured values based on the above definitions are summarized in Table 2 for all the test specimens.

Failure of the plain surface connection, Specimen 1NK4, was characterized by slip at the drypack-panel interface and the formation of a few cracks parallel to the load applied normal to the connection, as shown in Fig. 6. This be-
behavior indicated that the shear capacity of the plain surface connection was mainly dependent on the shear friction resistance at the drypack-panel interface. The cracking behavior of both the large and small multiple shear key connections was virtually identical, as shown in Fig. 6 for Specimens 1LK2 and 2SK2. After cracking, the behavior of these connections was characterized by crushing of the struts which formed between the diagonal cracks, and by slip along the crack surface.

**Effect of the Shear Key Configuration**

The behavior of the large and small key connections, Specimens 1LK2 and 2SK2, under an applied stress of 2 MPa...
Fig. 7. Effect of key configuration and level of preload.

(290 psi) normal to the connection, is given in Fig. 7. The similarity between the curves suggests that the difference between the two shear key configurations used in this study had no effect on the behavior or capacity of the connection.

The same behavior was also observed for Specimens 2LK4 and 1SK4 which were tested under a stress of 4 MPa (580 psi) normal to the connection, as shown in the same figure. The variation in the ultimate shear resistance of all the multiple shear key specimens, tested under the same load normal to the connection, was less than 15 percent.

An inspection of each connection after testing showed no evidence of bond between the drypack and the panel. This observation is also evident by the similarity of the load-slip curves for the bonded and unbonded large key connections, as shown in Fig. 7. The same behavior was observed for the bonded and unbonded small key connections, Specimens 1SK4 and 3SK4B, which were tested under a stress of 4 MPa (580 psi) normal to the connection.

**Effect of Load Normal to the Connection**

A comparison of the behavior of the large and small multiple shear key connections under the two stress levels of 2 and 4 MPa (290 and 580 psi) normal to the connection is also given in Fig. 7. The maximum shear capacity of the different shear key connections subjected to a stress of 4 MPa (580 psi) normal to the connection was 60 percent higher than that for similar specimens at the 2 MPa (290 psi) stress level.

This increase in shear capacity is attributed to the increase in confinement, and consequently the tensile resistance of the drypack, provided by the higher stress normal to the connection. The ul-
Table 2. Summary of measured shear strengths.

<table>
<thead>
<tr>
<th>Joint configuration</th>
<th>Specimen mark</th>
<th>Cracking load, $V_{cr}$ (kN)</th>
<th>Maximum load, $V_{m}$ (kN)</th>
<th>Ultimate shear resistance, $V_{u}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large key</td>
<td>1LK2</td>
<td>500</td>
<td>569</td>
<td>418</td>
</tr>
<tr>
<td></td>
<td>KRK4</td>
<td>800</td>
<td>867</td>
<td>688</td>
</tr>
<tr>
<td></td>
<td>3LK4B</td>
<td>1000</td>
<td>1058</td>
<td>624</td>
</tr>
<tr>
<td>Small key</td>
<td>2SK2</td>
<td>500</td>
<td>559</td>
<td>419</td>
</tr>
<tr>
<td></td>
<td>1SK4</td>
<td>803</td>
<td>884</td>
<td>622</td>
</tr>
<tr>
<td></td>
<td>3SK4B</td>
<td>807</td>
<td>893</td>
<td>648</td>
</tr>
<tr>
<td>Plain surface</td>
<td>1NK4</td>
<td>503</td>
<td>540</td>
<td>507</td>
</tr>
</tbody>
</table>

Note: 1 kN = 0.225 kip.

The above results show that the shear capacity does not increase by the same percentage as the increase in the level of stress normal to the connection. This suggests that the behavior of the shear key connection cannot be fully described by the simple shear friction theory, which states that the shear resistance is directly proportional to the level of stress normal to the connection.
Effect of Shear Keys

The behavior of the large and small shear key connections subjected to a stress of 4 MPa (580 psi) normal to the connection are compared to the plain surface connection, under the same level of stress, in Fig. 8. As expected, the presence of shear keys in the connection greatly enhances the shear capacity in comparison to the plain surface connection.

As a result of the interlocking action of the drypack shear keys, the maximum shear capacity of the multiple shear key connections was approximately 60 percent higher than that of the plain surface connection. The ultimate shear resistance of the multiple shear key connection was as much as 25 percent higher than that of the plain surface connection. The smaller increase in ultimate shear resistance, in comparison to the maximum load, is probably due to the presence of extensive diagonal cracks in the drypack shear keys.

Shear Capacity

(i) Plain Surface Connection

The ultimate shear resistance, $V_u$, can be predicted, based on the friction coefficient, $\mu$, the compressive stress normal to the connection, $\sigma_n$, and the cross-sectional area of the connection, $A_e$, according to the ACI and CSA Codes, as follows:

$$V_u = \mu \sigma_n A_e$$  \hspace{1cm} (1)

Based on the test results, a friction coefficient of 0.62 was computed. This value is consistent with that used in the ACI Code, but higher than the value of 0.5 recommended by the CSA Code. The value of 0.62 is also in agreement with the friction coefficient of $0.7 \pm 0.1$ which was determined in a previous study.

(ii) Multiple Shear Key Connection

The analytical methods developed in this section are solely for the shear de-
sign of multiple shear key connections. The presence of tensile stresses due to overturning moments could be accounted for by limiting the joint length to the compression stress block of the panel. However, in this research program it is assumed that under the effect of the various load combinations, the wall panels are post-tensioned so as to produce a net compressive stress along the length of the horizontal connection.

(A) Cracking Shear Load, $V_{cr}$

The proposed model for the cracking shear capacity, $V_{cr}$, is dependent on the combined action of the shear friction resistance, $V_f$, and the bearing resistance, $V_b$, along the sloped edge of the drypack shear keys as follows:

$$V_{cr} = V_f + V_b$$

(2)

The two possible shear friction paths associated with the multiple shear key connections tested in this study are shown in Fig. 9. The shear resistance according to the friction path described in Fig. 9(a) is based on the assumption that slip can occur along all the bearing surfaces.

This shear resistance can be calculated in terms of the shear key configuration, the friction coefficient, $\mu$, and the stress normal to the connection, $\sigma_n$, as follows:

$$V_f = \mu \sigma_n (A_e - n d t \tan \theta)$$

(3)

where

- $n$ = number of drypack shear keys
- $d$ = depth of shear key
- $t$ = thickness of connection
- $\theta$ = inclination of shear key to horizontal

The shear resistance according to the second friction path, Fig. 9(b), is based on the assumption that slip occurs only at the drypack-panel interface in the region between the drypack shear keys. This shear resistance may be estimated as:

$$V_f = \mu \sigma_n (A_e - n h t)$$

(4)

The bearing stress at the sloped edge of the shear keys induces a state of tensile stress in the shear keys. Thus, the bearing capacity, $V_b$, is ultimately controlled by the tensile strength of the drypack. The bearing component, $V_b$, may therefore be estimated as follows:

$$V_b = \sqrt{f_t (f_t + \sigma_n) A_{cr}}$$

(5)

where $f_t$ is the tensile strength of the drypack and $A_{cr}$ is the total cross-sectional area of the diagonal cracks in the drypack shear keys.

The tensile strength of the drypack, $f_t$, can be calculated based on the compressive strength, $f_c$, as:

$$f_t = 0.6 \sqrt{f_c}$$

(6)

The cross-sectional area of the diagonal cracks in the multiple shear key connection is calculated as:

$$A_{cr} = n t \sqrt{h^2 + l^2}$$

(7)

Consequently, two possible models could be used to predict the cracking shear strength of the multiple shear key connections as follows:

Model 1:

$$V_{cr} = \mu \sigma_n (A_e - n dt \tan \theta) + \sqrt{f_t (f_t + \sigma_n) A_{cr}}$$

(8)

Model 2:

$$V_{cr} = \mu \sigma_n (A_e - nht) + \sqrt{f_t (f_t + \sigma_n) A_{cr}}$$

(9)

The predicted cracking loads according to these two models are compared with the measured values in Fig. 10. This figure indicates that Model 1 provides better predictions of the cracking load. However, three of the six predictions were overestimated by 5 to 10 percent. The predictions based on Model 2 provide conservative estimates of the cracking load, especially at the higher levels of load normal to the connection.
(B) Maximum Shear Load, $V_m$

Based on the observed behavior after cracking, the maximum shear load, $V_m$, of the multiple shear key connection was mainly governed by the compressive strength of the struts between the diagonal cracks and the shear friction resistance along the slip surface, as illustrated in Fig. 11. Therefore, the predicted maximum shear load, $V_m$, can be expressed in terms of these two components as follows:

$$V_m = V_{me} + V_{mf}$$  \hspace{1cm} (10)

where $V_{me}$ is the shear resistance of the strut mechanism and $V_{mf}$ is the shear friction resistance along the slip surface.

In this analysis, the shear wall panels are assumed to act as rigid bodies connected by $n - 1$ struts, where $n$ is the number of shear keys. For the three keys in Fig. 11a, the struts are shown schematically in Fig. 11b. The compressive strength of the cracked drypack, $f_{cz}$, could be evaluated using Collins and Mitchell's equation:

$$f_{cz} = \frac{f_u}{0.8 + 170\varepsilon_1}$$  \hspace{1cm} (11)

where $\varepsilon_1$ is the average maximum principal tensile strain in the drypack at cracking.

For the multiple shear key connections tested in this study, the measured strain, $\varepsilon_1$, varied between 0.0026 and 0.004 strain. Using the maximum measured strain value of 0.004, $f_{cz}$ may be taken as $0.67f_u$ for these types of connections. Thus, the shear resistance of the strut mechanism, $V_{me}$, may be estimated as:

$$V_{me} = (n - 1)f_{cz}A_s \sin \alpha$$  \hspace{1cm} (12)

where $A_s$ is the average cross-sectional area of the diagonal portion of the strut and $\alpha$ is the inclination of the diagonal.
portion of the strut to the horizontal.

These two parameters may be computed in terms of the shear key dimensions as follows:

\[ A_{cs} = \frac{1}{2}(b + d)t \cos \theta \]  
\[ \alpha = \tan^{-1}(h/b) \]

Representing the connection by a rectangular strip, the distribution of forces at the connection, including the shear friction resistance, \( V_{mf} \), provided by slip along the drypack-panel interface and along the diagonal cracks, is shown in Fig. 11c. The shear friction re-

Fig. 11. Maximum shear strength model.
Based on the test results, the ultimate shear resistance of the multiple shear key connection mainly depends on the level of load normal to the connection, and the bearing stresses and shear friction along the slip surfaces. As discussed earlier, the configuration of the shear keys considered in this investigation was found to have an insignificant effect on the shear capacity.

Using a linear regression analysis, the following model was developed to predict the ultimate shear resistance of the multiple shear key connections in terms of the bearing and shear resistances:

\[
V_u = 0.2 \sqrt{f_y A_{ck}} + 0.5 \sigma_n A_c \tag{17a}
\]

\[
V_u = 2.4 \sqrt{f_y A_{ck}} + 0.5 \sigma_n A_c \tag{17b}
\]

for \(f_y, \sigma_n \) in psi; \(A_{ck}, A_c \) in in.\(^2\)

where \(A_{ck} \) is the cross-sectional area for the portion of the connection covered by the shear keys, and \(A_c \) is the cross-sectional area for the entire length of the connection. The area \(A_{ck} \) is equal to \(A_c \) if the shear keys cover the entire length of the connection. The above equation in-
indicates a lower value of 0.5 for the friction coefficient in comparison with the value of 0.62 obtained from the test results. This is probably due to the widening of the cracks in the connection at the ultimate resistance stage.

The predicted ultimate shear resistance, using Eq. (17), is compared to the measured values in Fig. 13.

Based on a study performed in France, Lacombe and Pommeret developed an equation to predict the ultimate shear resistance of multiple shear key connections. In applying this equation in the present study, the effect of external load perpendicular to the connection was considered to be equivalent to the clamping force due to continuity bars across the connection. The results obtained from Lacombe and Pommeret's equation and the proposed equation of the current study, Eq. (17), are compared to the test results in Table 3. Lacombe and Pommeret's equation overestimates the ultimate shear resistance of the test specimens by an average of 53 percent. Therefore, their equation may not be directly applicable to horizontal connections subjected to external compressive loads normal to the connection.

In the following, sample calculations for the results in Table 3 are provided. The configuration of the multiple shear key connection used in this calculation is shown in Fig. 14. U.S. customary units are used in the calculations.

Table 3. Comparison of test and calculated ultimate shear resistances.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( \frac{V_u^*}{V_{u,\text{test}}} )</th>
<th>( \frac{V_u^+}{V_{u,\text{test}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1LK2</td>
<td>0.99</td>
<td>1.68</td>
</tr>
<tr>
<td>2LK4</td>
<td>0.90</td>
<td>1.44</td>
</tr>
<tr>
<td>3LK4B</td>
<td>0.99</td>
<td>1.58</td>
</tr>
<tr>
<td>2SK2</td>
<td>0.99</td>
<td>1.54</td>
</tr>
<tr>
<td>1SK4</td>
<td>1.00</td>
<td>1.49</td>
</tr>
<tr>
<td>2SK4B</td>
<td>0.96</td>
<td>1.43</td>
</tr>
</tbody>
</table>

*Based on Eq. (17).
†Based on Lacombe and Pommeret's formula (Ref. 9).
SAMPLE CALCULATIONS

Data:
\( f' = 3910 \text{ psi (27 MPa)} \); \( \sigma_n = 580 \text{ psi (4 MPa)} \)

From Fig. 14, using the notation defined in this paper:

- \( h = 3.94 \text{ in.} \); \( d = 1.38 \text{ in.} \); \( L = 3.35 \text{ ft} \);
- \( t = 7.87 \text{ in.} \); \( n = 5 \).

From Eq. (17b):

\[
V_u = 2.4 \sqrt{f'_u} A_{eh} + 0.5 \sigma_n A_c,
\]

where \( A_{eh} = A_c \)

\[
= 2.4 \sqrt{3910} (7.87)(12) + 0.5 (580)(7.87)(12)/1000
\]

\[
= 41.6 \text{ kip/ft}
\]

For Specimen 2LK4:

\( \frac{V_u}{V_{ulte}} = 41.6/46.2 = 0.90 \)

Using Lacombe and Pommeret’s equation:

\[
V_u = 0.116 \sqrt{f'_u \{21.167 B (1.63 + 1.49E - 0.011E^2) + 11.47E^2\}}
\]

where

\[
B = nht/L = 5(3.94)(7.87)/3.35 = 46.3 \text{ in.}^2/\text{ft}
\]

\[
E = \sigma_n t = (0.580)(7.87)(12) = 54.8 \text{ kip/ft}
\]

\[
V_u = 0.116 \sqrt{3.910 \{ (21.167)(46.3)(1.63 + (1.49)(54.8) - (0.011)(54.8)^2) + 11.47(54.8)^2 \}}
\]

\[
= 66.4 \text{ kip/ft}
\]

For Specimen 2LK4:

\( \frac{V_u}{V_{ulte}} = 66.4/46.2 = 1.44 \)

CONCLUSIONS

Seven specimens, including two different multiple shear key configurations and one plain surface connection, were tested under static shear loading conditions to investigate the various limit states behavior of multiple shear key connections. The effects of different parameters, including the key configuration and the level of load normal to the connection, were determined.

Analytical models were developed to predict the shear capacity at the various limit states. The model predictions were compared with the test results. The proposed models are mainly applicable where the effect of various load combinations produces a net compressive stress along the length of the horizontal connection.

Based on the results of the study, the following conclusions are drawn:

1. The presence of shear keys in the horizontal connection enhances the shear capacity in comparison to the plain surface connection.
2. The difference in the shear key configurations considered in this study had an insignificant effect on the behavior or capacity of the connection.
3. An increase in the level of load normal to the multiple shear key connection increases the shear capacity of
the connection. The percentage increase in shear capacity is, however, not equal to the percentage increase in load normal to the connection.

4. The cracking load may be conservatively estimated using the proposed model given in Eq. (9).

5. The equation based on the study performed in France does not appear to be directly applicable to horizontal connections subjected to external compressive loads normal to the connection.

6. The proposed models for the prediction of maximum shear load, Eq. (16), and ultimate shear resistance, Eq. (17), compare well with the test results.

ACKNOWLEDGMENTS

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The authors are grateful to the reviewers of the PCI JOURNAL for their constructive comments and particularly to Dr. Alex Aswad for bringing the French investigation (see Ref. 9) to their attention.

REFERENCES


APPENDIX — NOTATION

\[ A_c = \text{cross-sectional area for entire length of connection} \]
\[ A_{cr} = \text{cross-sectional area for portion of connection covered by shear keys} \]
\[ A_{cr} = \text{cross-sectional area of diagonal cracks} \]
\[ A_{cs} = \text{cross-sectional area of diagonal portion of a strut} \]
\[ B = \text{ratio of key area to joint length} \]
\[ b = \text{minimum space between individual panels} \]
\[ d = \text{depth of drypack shear key} \]
\[ E = \text{total force normal to connection} \]
\[ f_{ca} = \text{compressive strength of cracked drypack} \]
\[ f'_c = \text{specified compressive strength of concrete} \]
\[ f'_d = \text{compressive strength of drypack} \]
\[ f_t = \text{tensile strength of drypack} \]
\[ h = \text{height of drypack shear key} \]
\[ L = \text{length of connection} \]

\[ n = \text{number of drypack shear keys} \]
\[ t = \text{thickness of connection} \]
\[ V_b = \text{bearing resistance at drypack shear keys} \]
\[ V_{cr} = \text{cracking shear capacity} \]
\[ V_f = \text{shear friction resistance} \]
\[ V_m = \text{maximum shear capacity} \]
\[ V_{me} = \text{shear resistance of strut mechanism} \]
\[ V_{mf} = \text{shear friction resistance at maximum load} \]
\[ V_n = \text{nominal shear capacity} \]
\[ \alpha = \text{inclination of diagonal portion of strut to horizontal} \]
\[ \varepsilon_1 = \text{maximum tensile strain at cracking} \]
\[ \theta = \text{inclination of shear key to horizontal} \]
\[ \sigma_n = \text{compressive stress normal to connection} \]
\[ \mu = \text{friction coefficient} \]

NOTE: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by December 1, 1989.