Seismic Interaction of Flexural Ductility and Shear Capacity

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Introduction
Introduction

GLOBAL SEISMIC HAZARD MAP

- Not only applicable in US or Taiwan
- Research has worldwide implications

http://research.education.purdue.edu/challenge/hypermedia/04_05/Bill_Combs/New_Madrid/history.htm
Computer Modeling System
Cyclic Softened Membrane Model (CSMM)

- UH preformed significant amount of research to predict shear behavior
- Most recent model proposed by Mansour and Hsu in 2005, CSMM
- Accurately predicts cyclic shear behavior
“Simulation for Reinforced Concrete Structures” (SRCS)

• CSMM was implemented into a finite element framework, OpenSees
• A non-linear finite element computer program, SRCS, was developed by Zhong and Mo in 2005
SRCS Accuracy and Parametric Studies

- Accuracy of program proven by comparing real data to predicted outcomes
- Accuracy allowed that series of tests be completed using SRCS instead of experimental results to develop relationship
- Preferred over experimenting because of cost and time constraints
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Seismic Loading
Envelope Curve

Specimen PI2
Determination of Ductility and Shear Capacity
Determination of Deflection at First Yield

- Determine 75% of the maximum force and corresponding deflection

![Graph showing force vs. deflection](image)
Determination of Deflection at First Yield

- Determine 75% of the maximum force and corresponding deflection
- Draw a line through this point and the origin
Determination of Deflection at First Yield

- Determine 75% of the maximum force and corresponding deflection
- Draw a line through this point and the origin
- Find the deflection along this line that corresponds with the maximum force
Determination of Deflection at Ultimate Point

- Determine 80% of the maximum force and corresponding deflection along the descending branch of the curve
Flexural Ductility and Shear Strength

- Ductility is assumed to be the ratio of the deflection at the ultimate point to the deflection at the first yield point.
- The shear strength was assumed to be 80% of the maximum strength.
Flexural Ductility and Shear Strength

- Each envelope curve represents one point on Ductility vs. Shear plot.
- More than 200 points obtained for study.
- Points connected to represent relationships determined in parametric studies.
Previous Models

• Previously defined models analyzed for this study were proposed by the following institutions:
  – American Concrete Institute (ACI)
  – California Department of Transportation (Caltrans)
  – University of California San Diego (UCSD)
  – University of Southern California (USC)
  – University of California Berkeley (UCB)
Previous Models

- Applicable shear strength models plotted with actual shear strength
- No model is accurate for all given points
- Accuracy measured by taking the actual shear strength divided by the shear strength proposed by the model
Accuracy of Previous Models
Normal Strength Concrete
Accuracy of Previous Models
High Strength Concrete

ACI Accuracy Based on Ductility

Caltrans Accuracy Based on Ductility

UCSD Accuracy Based on Ductility

USC Accuracy Based on Ductility

UCB Accuracy Based on Ductility
Proposed Models

- Normal Strength Concrete Model
- High Strength Concrete Model
- Universal Model
Normal Strength Concrete Model
Normal Strength Concrete Model

\[ V_n = V_c + V_p + V_s \]

- \( V_n \) = nominal shear strength
- \( V_c \) = nominal shear strength provided by the concrete
- \( V_p \) = nominal shear strength provided by the axial load
- \( V_s \) = nominal shear strength provided by the shear reinforcement
Concrete Contribution to Shear

\[ V_c = k \sqrt{f'_c A_e} \]

- \( V_c \) = nominal shear strength provided by the concrete, N
- \( k \) = influence factor for flexural ductility
- \( f'_c \) = specified compressive strength of the concrete, MPa
- \( A_e \) = 80% of the cross-sectional area, mm²
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

- Increased Stirrup Ratio
- Increased Longitudinal Steel Ratio
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

ACI
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

UCSD
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

UCB
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

USC
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

- Force (Force vs. Ductility graph)
- Ductility (Levels of Ductility vs. Shear Capacity graph)
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

- Force
- Ductility
Determination of Influence Factor for Flexural Ductility

\[ q = \begin{cases} 
-144 \rho_t + 5.3 & \text{for } \rho_t \leq 0.01 \\
3.85 & \text{for } \rho_t > 0.01 
\end{cases} \]

- \( q \) = upper limit of flexural ductility beyond which the shear capacity remains constant
- \( \rho_t \) = stirrup ratio, decimal
Determination of Influence Factor for Flexural Ductility
Determination of Influence Factor for Flexural Ductility

\[ r = -13300 \rho_t^2 + 242 \rho_t + 2.8 \quad \text{for} \quad \rho_t \leq 0.01 \]
\[ r = 3.85 \quad \text{for} \quad \rho_t > 0.01 \]

- \( r \)=flexural ductility at which rate of decrease of shear capacity with flexural ductility changes
- \( \rho_t \)=stirrup ratio, decimal
Determination of Influence Factor for Flexural Ductility

\[ k = 0.29 \quad \text{for } \mu \leq 2 \]
\[ k = 0.53 - 0.12\mu \quad \text{for } 2 < \mu \leq r \]
\[ k = 0.53 - 0.095r - 0.025\mu \quad \text{for } r < \mu \leq q \]
\[ k = 0.53 - 0.095r - 0.025q \quad \text{for } \mu > q \]

- k = influence factor for flexural ductility
- \( \mu \) = flexural ductility
- r = flexural ductility at which rate of decrease of shear capacity with flexural ductility changes
- q = upper limit of flexural ductility beyond which the shear capacity remains constant
Axial Load Contribution to Shear

\[ V_p = \frac{D - c}{2000a} \times P \]

- \( V_p \) = nominal shear strength provided by the axial load, N
- \( D \) = the overall section depth, mm
- \( c \) = the depth of the compression zone, mm
- \( a \) = the ratio of the moment to the shear at the critical section, mm
- \( P \) = the factored axial load normal to the cross section occurring simultaneously with the factored shear force at the section, N
Steel Contribution to Shear

\[ V_s = \left(3300 \frac{V_s^3}{\rho_t^3} - 1\right) \rho_t b_w f_{yh} \left(\frac{d - c}{2 \rho_t}\right) b_w f_{yh} (d - c) \cot \theta \]

Other Models

- \( V_s \)=nominal shear strength provided by the steel, N
- \( \rho_t \)=stirrup ratio, decimal
- \( b_w \)=width of the web, mm
- \( f_{yh} \)=yield strength of the transverse steel, MPa
- \( d \)=distance from the extreme tension fiber to the centroid of the longitudinal tension reinforcement, mm
- \( c \)=depth of the compression block, mm
- \( \theta \)=angle of principal shear crack to column axis, can be assumed to be 30 degrees
Accuracy of Previous Models
Normal Strength Concrete
High Strength Concrete Model
High Strength Concrete Model

\[ V_n = V_c + V_p + V_s \]

- \( V_n \) = nominal shear strength
- \( V_c \) = nominal shear strength provided by the concrete
- \( V_p \) = nominal shear strength provided by the axial load
- \( V_s \) = nominal shear strength provided by the shear reinforcement
Concrete Contribution to Shear

\[ V_c = k \sqrt{f_c'} A_e \]

- \( V_c \) = nominal shear strength provided by the concrete, N
- \( k \) = influence factor for flexural ductility
- \( f_c' \) = specified compressive strength of the concrete, MPa
- \( A_e \) = 80\% of the cross-sectional area, mm\(^2\)
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

Ductility vs. Force
Determination of Influence Factor for Flexural Ductility
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

Force

Ductility
Determination of Influence Factor for Flexural Ductility

\[ q = -144 \rho_t + 6 \quad \text{for} \quad q \geq r \]

\[ q = r \quad \text{for} \quad q < r \]

- \( q \)=upper limit of flexural ductility beyond which the shear capacity remains constant
- \( \rho_t \)=stirrup ratio, decimal
- \( r \)=flexural ductility at which rate of decrease of shear capacity with flexural ductility changes
Determination of Influence Factor for Flexural Ductility

Typical Ductility vs. Shear Capacity

- Force vs. Ductility graph
  - Force values: 0, 5000, 10000, 15000, 20000, 25000
  - Ductility values: 0, 1, 2, 3, 4, 5, 6, 7
Determination of Influence Factor for Flexural Ductility

\[ r = 35 \rho_t + 3.2 \]

- \( r \) = flexural ductility at which rate of decrease of shear capacity with flexural ductility changes
- \( \rho_t \) = stirrup ratio, decimal
Determination of Influence Factor for Flexural Ductility

\[ k = 0.29 \quad \text{for } \mu \leq 2 \]
\[ k = 0.53 - 0.12\mu \quad \text{for } 2 < \mu \leq r \]
\[ k = 0.53 - 0.095r - 0.025\mu \quad \text{for } r < \mu \leq q \]
\[ k = 0.53 - 0.095r - 0.025q \quad \text{for } \mu > q \]

- \( k \)=influence factor for flexural ductility
- \( \mu \)=flexural ductility
- \( r \)=flexural ductility at which rate of decrease of shear capacity with flexural ductility changes
- \( q \)=upper limit of flexural ductility beyond which the shear capacity remains constant
Axial Load Contribution to Shear

\[ V_p = \frac{D - c}{2000a} P \]

- \( V_p \) = nominal shear strength provided by the axial load, N
- \( D \) = the overall section depth, mm
- \( c \) = the depth of the compression zone, mm
- \( a \) = the ratio of the moment to the shear at the critical section, mm
- \( P \) = the factored axial load normal to the cross section occurring simultaneously with the factored shear force at the section, N
Steel Contribution to Shear

\[ V_s = \left(4000\rho_t^3 - 133\rho_t^2 + 1.4\rho_t\right)b_w f_{yh} (d - c) \cot \theta \]

- \( V_s \) = nominal shear strength provided by the steel, N
- \( \rho_t \) = stirrup ratio, decimal
- \( b_w \) = width of the web, mm
- \( f_{yh} \) = yield strength of the transverse steel, MPa
- \( d \) = distance from the extreme tension fiber to the centroid of the longitudinal tension reinforcement, mm
- \( c \) = depth of the compression block, mm
- \( \theta \) = angle of principal shear crack to column axis, can be assumed to be 30 degrees
Accuracy of Previous Models
High Strength Concrete

ACI Accuracy Based on Ductility

Caltrans Accuracy Based on Ductility

Proposed Model Accuracy Based on Ductility

UCSD Accuracy Based on Ductility

USC Accuracy Based on Ductility
Universal Model
Universal Model

\[ V_n = V_c + V_p + V_s \]

- \( V_n \) = nominal shear strength
- \( V_c \) = nominal shear strength provided by the concrete
- \( V_p \) = nominal shear strength provided by the axial load
- \( V_s \) = nominal shear strength provided by the shear reinforcement
Concrete Contribution to Shear

\[ V_c = k \sqrt{f'_c A_e} \]

- \( V_c \) = nominal shear strength provided by the concrete, N
- \( k \) = influence factor for flexural ductility
- \( f'_c \) = specified compressive strength of the concrete, MPa
- \( A_e \) = 80% of the cross-sectional area, mm\(^2\)
Determination of Influence Factor for Flexural Ductility

\[ q = \begin{cases} 
-144\rho_t + 0.03 f'_c + 4.3 & \text{for } q \geq r \\
q = r & \text{for } q < r 
\end{cases} \]

- \( q \) = upper limit of flexural ductility beyond which the shear capacity remains constant
- \( \rho_t \) = stirrup ratio, decimal
- \( f'_c \) = specified compressive strength of the concrete, MPa
- \( r \) = flexural ductility at which rate of decrease of shear capacity with flexural ductility changes
Determination of Influence Factor for Flexural Ductility

\[ r = 35 \rho_t - 0.011 f'_c + 3.8 \]

- \( r \) = flexural ductility at which rate of decrease of shear capacity with flexural ductility changes
- \( \rho_t \) = stirrup ratio, decimal
- \( f'_c \) = specified compressive strength of the concrete, MPa
Determination of Influence Factor for Flexural Ductility

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- \( k \) = influence factor for flexural ductility
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- P = the factored axial load normal to the cross section occurring simultaneously with the factored shear force at the section, N
Steel Contribution to Shear

\[ V_s = \left(3200 \rho_t^3 - 110 \rho_t^2 + 1.2 \rho_t \right) b_w f_{yh} (d - c) \cot \theta \]

- \( V_s \) = nominal shear strength provided by the steel, N
- \( \rho_t \) = stirrup ratio, decimal
- \( b_w \) = width of the web, mm
- \( f_{yh} \) = yield strength of the transverse steel, MPa
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Accuracy of Previous Models
High Strength Concrete

Accuracy

UCSD Accuracy Based on Ductility

ACI Accuracy Based on Ductility

Caltrans Accuracy Based on Ductility

UCB Accuracy Based on Ductility

USC Accuracy Based on Ductility
Conclusions

1. SRCSE is capable of accurately predicting the nonlinear behavior of reinforced concrete structures subjected to various loading situations.

2. There are several models available that predict the relationship between flexural ductility and shear strength; however, the accuracy of these models is doubtful due to either over- or under-estimations. Hence, they cannot be used in practice.

3. The proposed models can accurately predict the relationship between flexural ductility and shear strength.
Questions?