Simplified Collapse Analysis of Structures using the Extended Distinct Element Method and F.E.M Mapped Spring Network

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Outline

• Introduction
• Objective
• Numerical Analysis
• Future work
Introduction
Introduction

• Reinforced Concrete frame with masonry infill (R.C.M.I)
Introduction

• Problems to be addressed
  • Susceptibility to disaster

  – Very common building type in developing countries
  – Non-engineered buildings
  – Non-compliance of seismic building codes
  – Extremely high population density
  – Very bad performance in past earthquakes
Introduction

• Problems to be addressed
  • Vulnerability assessment

  – Because of highly random nature of material properties very difficult to assess building behavior

  – Lack of proper compliance leading to many non-engineered defects

  – Existing scientific tools to assess vulnerability are usually computationally expensive and complex for practical usage by working professionals
Objective
Objective

To assess the seismic vulnerability of existing R.C.M.I buildings using an effective and accurate numerical analysis.
Objective

• Vulnerability
  – Building response during a disaster that affects

• Human activities (Evacuation)
  – Spalling of masonry elements
  – Failure of structural elements
  – Blockage of evacuation path

• Loss of human lives
  – Partial collapse of building
  – Complete collapse
Objective

To **assess the seismic vulnerability** of existing R.C.M.I buildings using an **effective and practical numerical analysis tool** through an **user-friendly interface**

- Numerical analysis of R.C.M.I buildings
- Analysis of existing buildings
- Verification and Validation
- Develop tool for easy analysis / visualization
Numerical Analysis
Numerical analysis

Discrete element method

Solution scheme

Explicit
Implicit

Element shape

Sphere
Cube/cuboid
Voronoi / Delaunay tetrahedral
Ellipsoidal
Elements used in F.E.M

Element deformability

Static
Dynamic
Rigid
Deformable

Contact

Hard
Soft

Analysis
Numerical analysis: Existing schemes

- Distinct element method [D.E.M/E.D.E.M]
- Applied Element Method [A.E.M]
- Discontinuous Deformation Analysis [D.D.A]
- Combined D.E.M and F.E.M
- Rigid Body Spring Model [R.B.S.M]

Contact

Solution scheme

Discrete element method

Element shape

- Sphere
- Cube/cuboid
- Voronoi / Delaunay tetrahedral
- Ellipsoidal

Elements used in F.E.M

Analysis

Element deformability

- Static
- Dynamic
- Rigid
- Deformable
Contact

• The Contact Problem
  – Contact detection plays a significant role in 3-D collapse analysis using discrete elements
  – If the contact detection is simplified (e.g. sphere) the overall computation time reduces drastically

<table>
<thead>
<tr>
<th>Function name</th>
<th>Time in Self [m/s]</th>
<th>% of Total</th>
<th>Function Calls</th>
</tr>
</thead>
<tbody>
<tr>
<td>simulation housekeeping</td>
<td>77.20</td>
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<td>1000</td>
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<tr>
<td>CONTACT DETECTION</td>
<td></td>
<td></td>
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<tr>
<td>spatial search</td>
<td>1197.89</td>
<td>60%</td>
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<td>resolve geometry</td>
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<td>penalty force</td>
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<td>3.6%</td>
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<tr>
<td>Newtonian physics</td>
<td>156.72</td>
<td>8%</td>
<td>1157239</td>
</tr>
</tbody>
</table>

>80% computation time spent on contact detection

Table from Discrete Element Simulation and the Contact Problem Williams[1999]
Preferable Properties

**DISCRETE ELEMENT METHOD**

- **SOLUTION SCHEME**
  - Implicit
  - Explicit

- **ELEMENT SHAPE**
  - Sphere
  - Cube/cuboid
  - Voronoi / Delaunay tetrahedral
  - Ellipsoidal

- **CONTACT**

- **ANALYSIS**

- **ELEMENT DEFORMABILITY**
  - Static
  - Dynamic
  - Rigid
  - Deformable

**Elements used in F.E.M**

- **Hard**
  - Sound state to complete collapse
  - Lesser computation cost
  - Accuracy
  - Modelling ease

- **Soft**
Numerical analysis: Proposed scheme

Essentially an improvement on the existing Extended Distinct Element Method

- Implicit
- Explicit
- Solution scheme
- Element shape
- Sphere
- Cube/cuboid
- Voronoi / Delaunay tetrahedral
- Ellipsoidal
- Elements used in F.E.M

- Hard
- Soft
- Contact

- Analysis
- Element deform-ability
- Static
- Dynamic
- Rigid
- Deformable
Extended Distinct Element method
Extended Distinct Element Method

Pore Springs

Contact Springs
Extended Distinct Element Method

Initialize and define contact

Check contact and compute contact spring force

Next time step

\[ M\ddot{u} + f_{spring}(u) + f_{damp}(\dot{u}) = f_{ext} \]

\[ \ddot{u} = M^{-1}(f_{ext} - f_{spring}(u) - f_{damp}(\dot{u})) \]

Calculate \( u \) and \( \dot{u} \) in next time step using Central difference scheme

Apply load increment

Explicit Dynamics
Extended Distinct Element Method

Extended Distinct Element Method

• Advantages of EDEM
  – Very simple
    • Modelling
    • Contact detection
    • Nonlinearity (Geometric and material)
  – No requirement to form Stiffness matrix
  – No requirement to solve large simultaneous equations (No matrix inversion required)
  – Lumped mass makes inertial forces computation very simple and mass matrix inversion trivial
Extended Distinct Element Method

• Disadvantages

  – Conditional stability of analysis (CFL condition) i.e. the solution scheme is stable only for a very small value of time step $\Delta t$

  – Not very accurate for elastic analysis due to arbitrary spring constants (Lack of proper solid mechanics theory)

  – Poisson ratios effect is neglected
## Extended Distinct Element Method

- **Proposed improvement**

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small time step</td>
<td>• Usage of a combine implicit-explicit numerical scheme</td>
</tr>
<tr>
<td></td>
<td>• Improve accuracy of elements thereby reducing number of elements required</td>
</tr>
<tr>
<td></td>
<td>• Optimize time step</td>
</tr>
<tr>
<td></td>
<td>• Usage of parallel computation</td>
</tr>
<tr>
<td>Accuracy in elastic range</td>
<td>Adoption of Finite element stiffness</td>
</tr>
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<td></td>
<td>Mapped Spring Network Model</td>
</tr>
<tr>
<td>Poisson ratio</td>
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</tbody>
</table>
Extended Distinct Element Method

• Proposed improvement

**State 1**
- Represents continuum deformation until spring tensile rupture

**State 2**
- Compressive, shear, and contact forces between the ruptured springs

**Complete Structural Analysis**

**Elastic**
- Non-linear
- Cracking

**Implicit Dynamics**
- Tangent stiffness matrix assembled every time step
- Larger time step
- Accurate and stable

**Explicit Dynamics**
- No stiffness matrix assembly required
- Smaller time step
- Good for contact detection (collision separation and collapse)
Full Analysis Plan

Seismic Loading

Building State
- Normal State
- Damaged State
- Collapsed State

Analysis Stage
- Linear
- Non-linear
- Cracking
- Separation
- Collapse

Analysis Phase
- PHASE I MAPPED SPRING NETWORK
- PHASE II EXTENDED DISTINCT ELEMENT METHOD

Numerical Scheme
- Implicit
- Explicit

Spring Type
- Only pore springs
- Pore + contact springs
Spring network system with Finite Element Mapping
Area computation

• Proposed method

\[
K = \int [B]^T [D] [B] dV
\]

\[
[F] = [K][U]
\]

\[
[\sigma] = [D][\varepsilon]
\]

\[
[\varepsilon] = [B][U]
\]
• Advantages of proposed scheme
  – With the derived spring constants, convergence and accuracy same as that of F.E.M
  – As a stiffness matrix is assembled, an implicit numerical scheme can be used in the initial phase leading to larger time step
  – Higher order elements can be used for derivation of stiffness matrix for better accuracy
  – Poisson ratio is implicitly included
  – Once explicit phase is activated, very large deformation, separation and collision can be followed effectively
  – The round elements make contact detection trivial
Concrete modelling
Spring Classification

Based on Spring type:
- Inner edge
- Inner diagonal
- Outer edge

Based on Material:
- Concrete
- Steel

Cracked phase:
- RC Zone

Pre-cracked phase:
- PC Zone
Concrete model

Compression model

Shear model

Tension model

Steel model

Conclusion
Conclusion

• The research involves development of a numerical tool used for collapse simulation with the following advantages
  – Model complete collapse of a building
  – Simple modelling
  – Computationally less expensive
  – Easy to use interface
  – Appealing visualization
Future work

I. FEM mapping Spring constant derivation

II. Linear Analysis

III. Non-linear Analysis

IV. Combined Implicit-Explicit computation

V. Complete collapse analysis

VI. 3D extension

VII. Interface creation

VII. Parametric study

Static

Modal

Dynamic

Geometric

Material

Concrete

Masonry
Acknowledgement
Thank You