Seismic behaviour of RC buildings infilled with masonry walls

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Seismic behaviour of RC buildings infilled with masonry walls

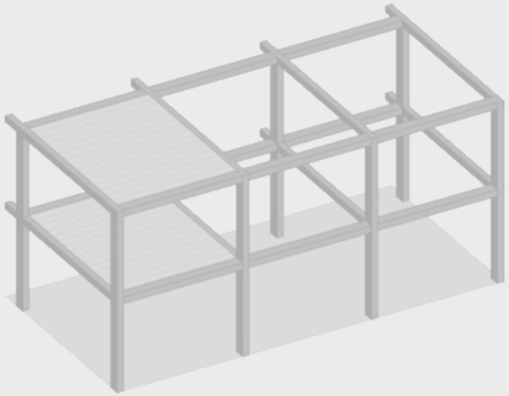
Motivation

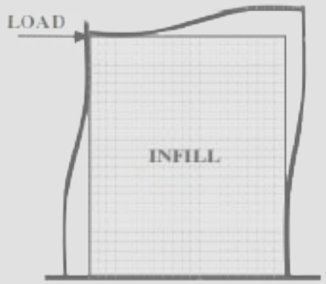
Literature review

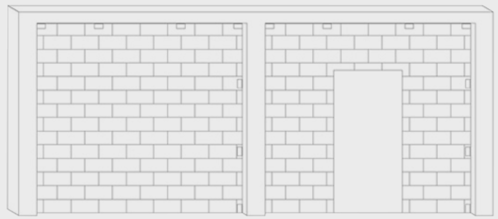
Damage assessment

Numerical modelling

Seismic risk = Hazard ∗ Vulnerability ∗ Exposure







Structural elements

Interaction

Non-structural elements

Boundary (foundation, soil, pounding,…)

(Benutzer, 2005; Azmat et al., 2013; Tucker, 2012)

Literature review

Lessons from earthquakes	~20
Seismic standards	~20
Experimental work	~125
Numerical modelling	~70

Low quality of materials

Insufficient constructive detailing

Insufficient shear strength

Vulnerability of infill walls

Collapses: Due to irregularities on the distribution of the infill walls

Literature review

Lessons from earthquakes	~20
Seismic standards	~20
Experimental work	~125
Numerical modelling	~70

Irregularities in height and plan (structural and non-structural elements)

Minimal strength capacity for the infill walls

Recommendations regarding positioning of openings on infill walls

Literature review

Lessons from earthquakes	~20
Seismic standards	~20
Experimental work	~125
Numerical modelling	~70

Gaps on infill-frame interface decreases considerably the horizontal strength

Vertical loading on columns increase of stiffness and resistance of the system due to increase of confinement of the wall

Eccentricity of the wall relative to the frame plane centre-line leads to out-of-plane bending effects, reducing both initial stiffness and ultimate capacity

Literature review

Lessons from earthquakes	~20
Seismic standards	~20
Experimental work	~125
Numerical modelling	~70

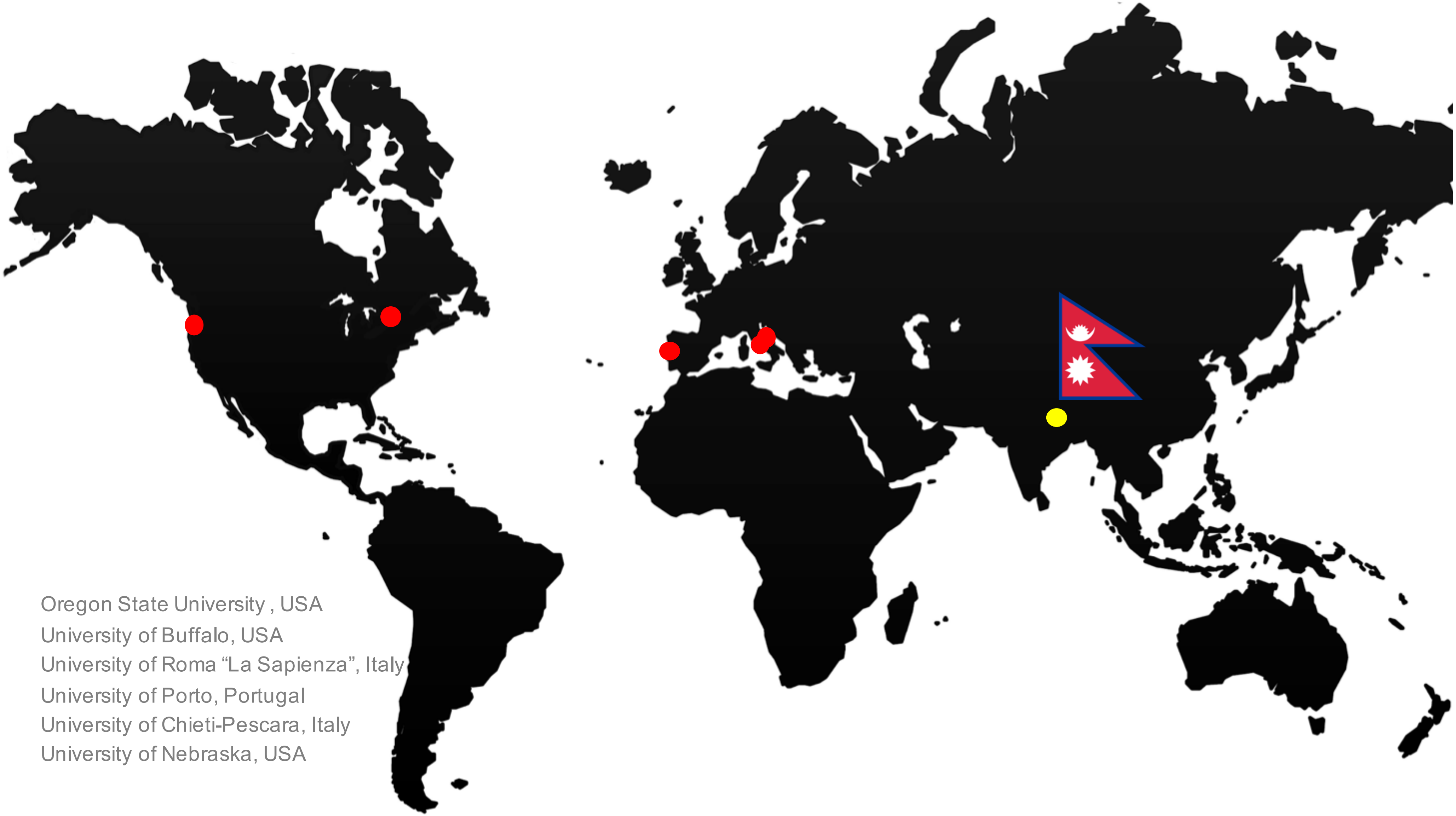
Models with combined in-plane and out-of-plane's behaviour

  Failure curve of infill masonry walls for actions in both directions

Parametric studies (and experimental) of double-leaf walls

Calibration of simplified models for retrofitting interventions

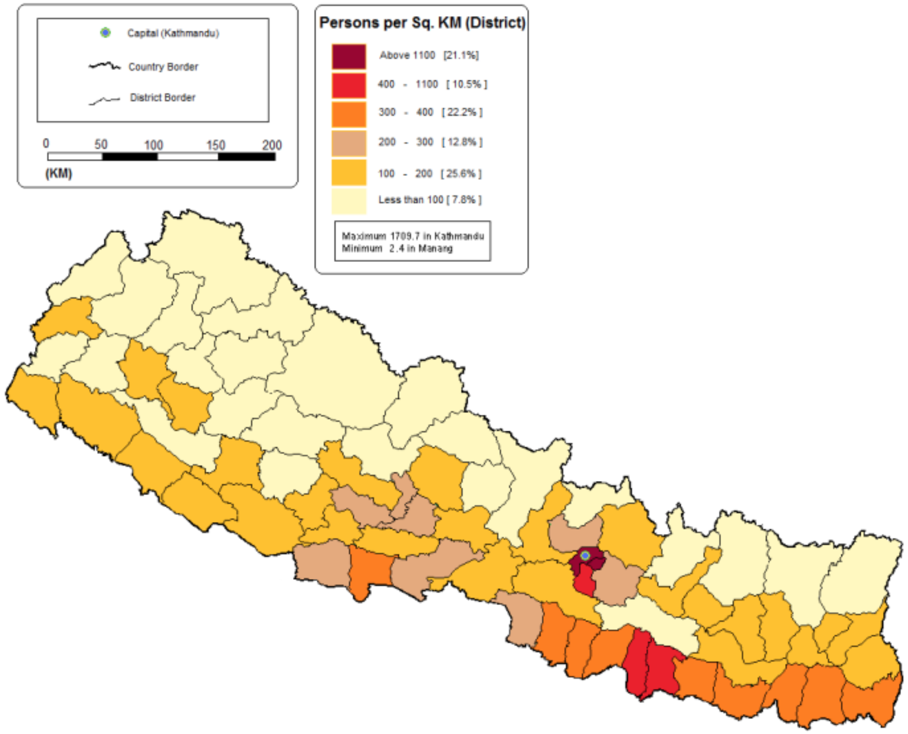
NSF RAPID | Damage Assessment



Oregon State University , USA
University of Buffalo, USA
University of Roma “La Sapienza”, Italy
University of Porto, Portugal
University of Chieti-Pescara, Italy
University of Nebraska, USA

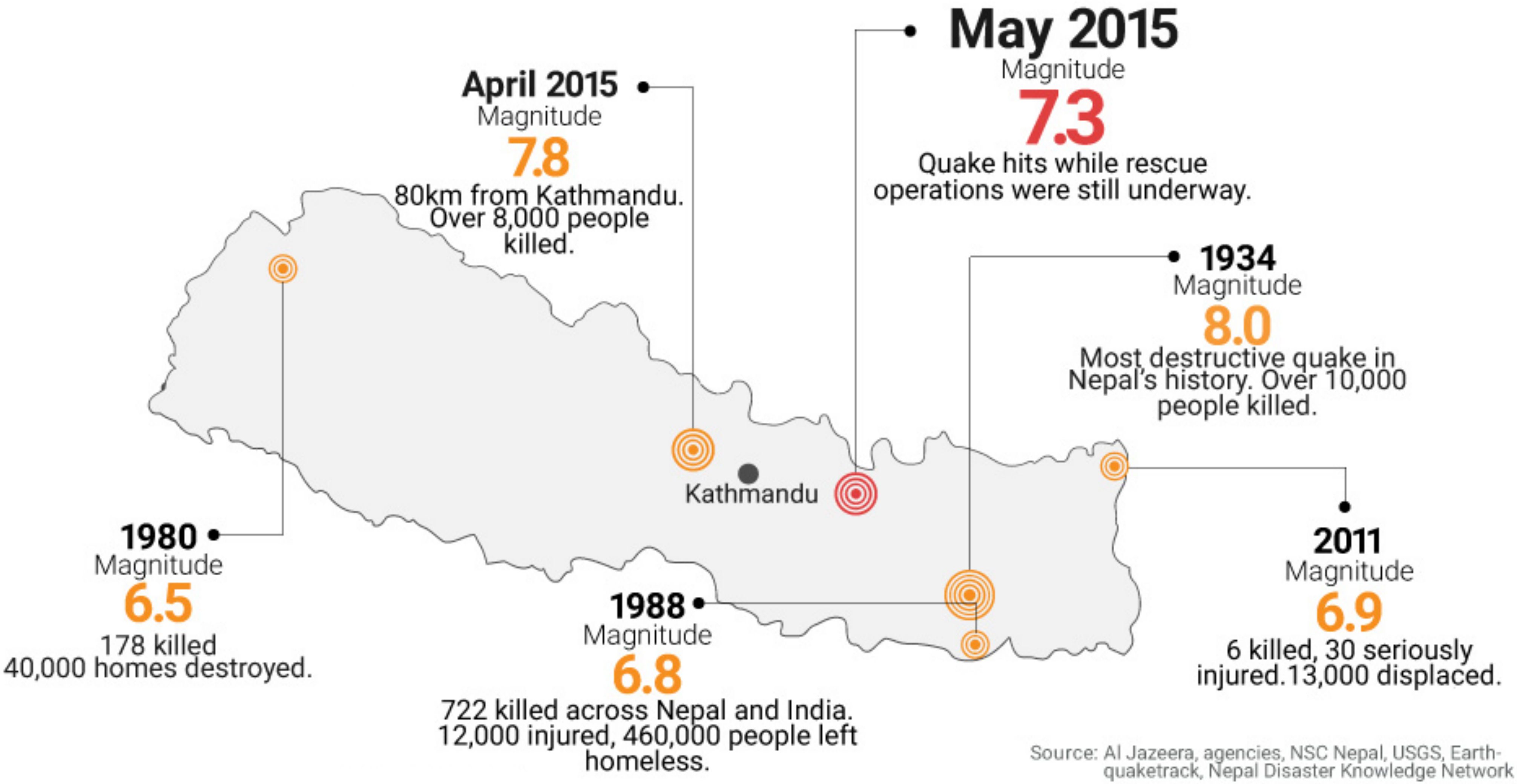
About Nepal | DAMAGE ASSESSMENT

Capital	Kathmandu (largest city)
Total Area	147,181 km^2 (1,6x PT)
Population	28,120,000 (2,7x PT)
Density	180/km^2
GDP	19.77 USD Billion (8% PT)



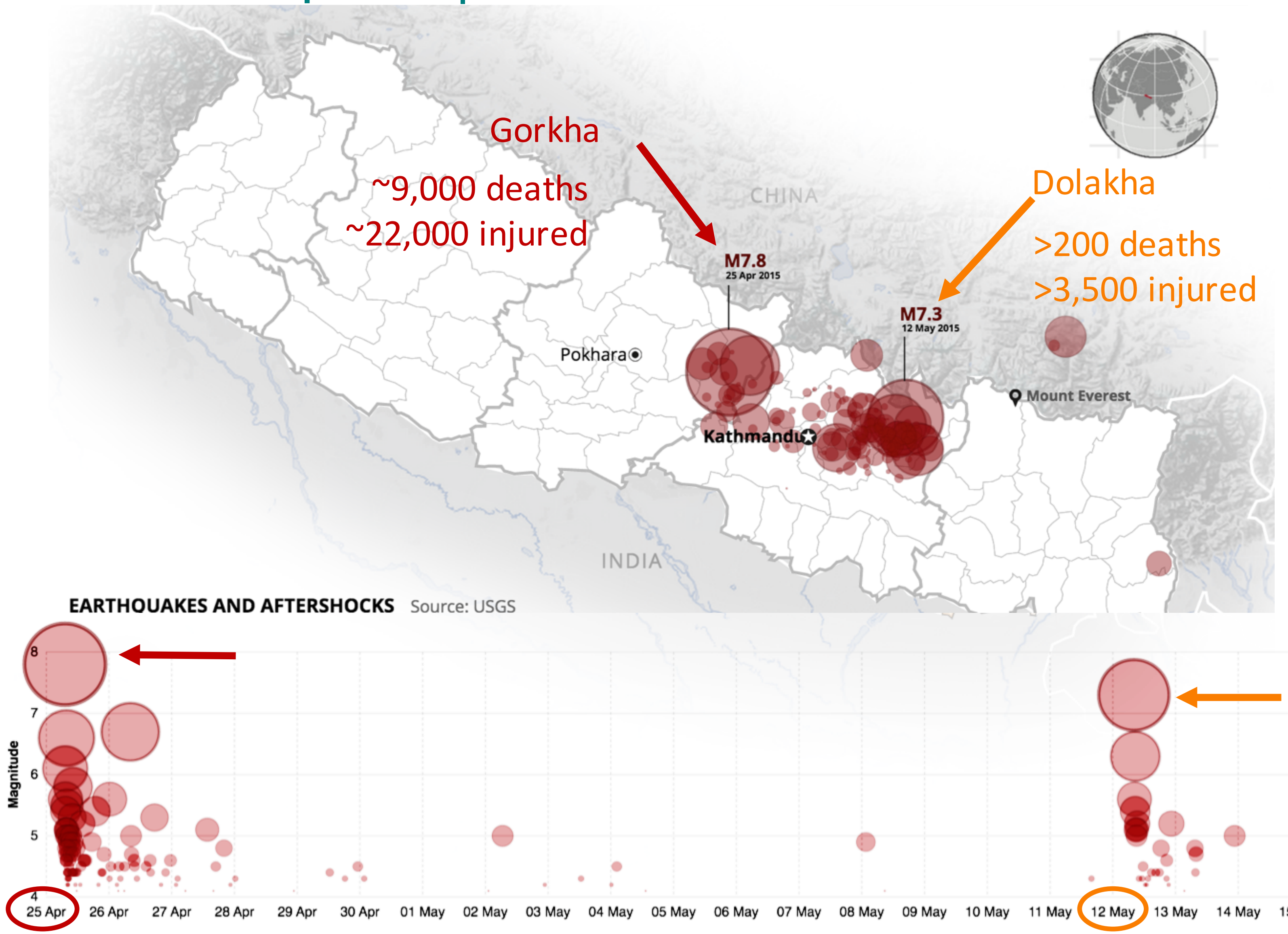
Sources:
wikimedia.org
tradingeconomics.com

Past earthquakes | DAMAGE ASSESSMENT



Hazard | Exposure | Some of the strongest registered earthquakes

Gorkha earthquake | DAMAGE ASSESSMENT



More than 400 aftershocks with M>4 | Location of seismic activity

Buildings typologies | DAMAGE ASSESSMENT

The buildings' stock of RC framed structures in Kathmandu valley is 38% and in Nepal 10%.

Over the last few decades (1991-2001), RC building construction has rapidly increased, replacing other construction materials and solutions, like adobe, stone and brick masonry, in Kathmandu Valley.

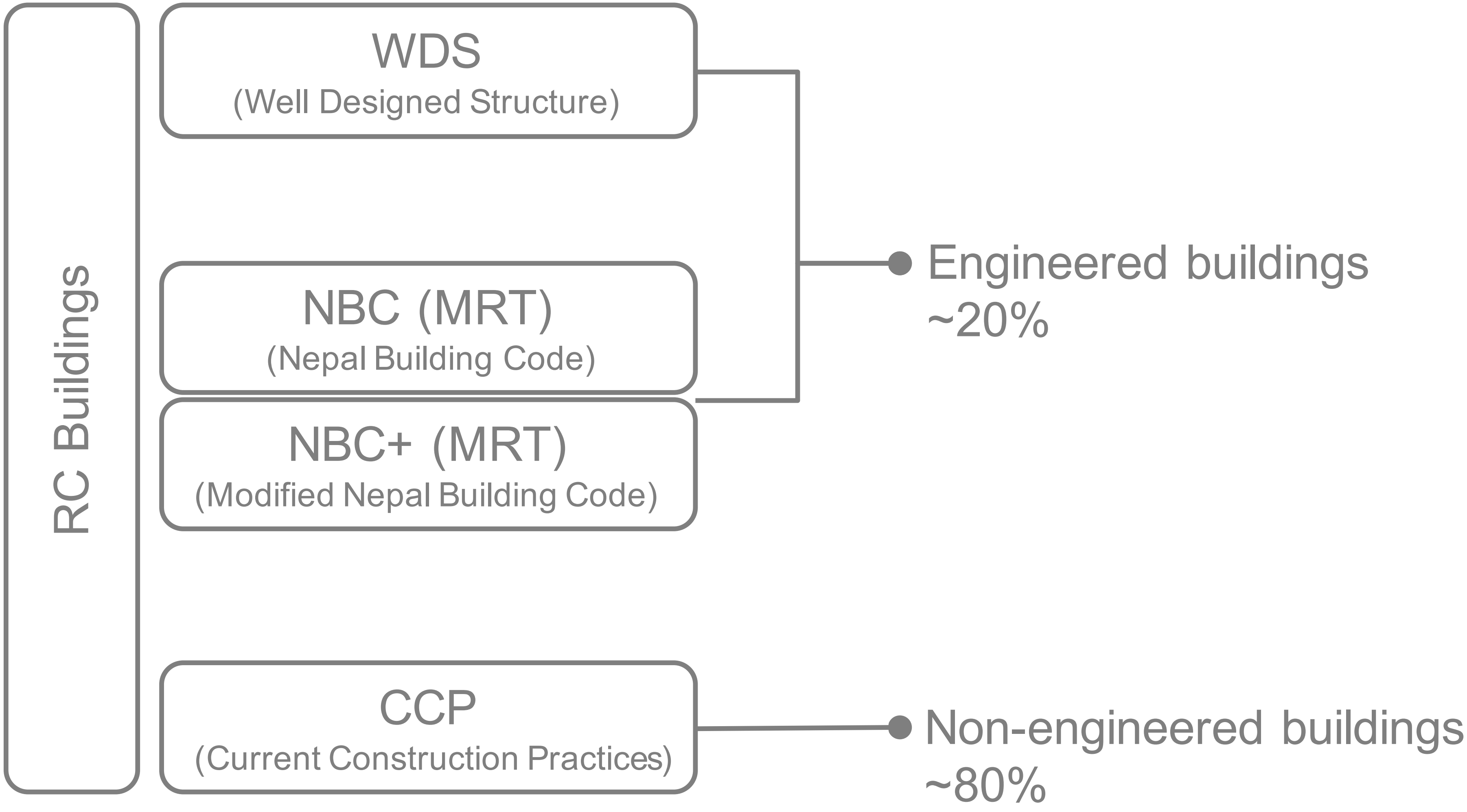
Most RC buildings in Nepal were constructed with framed structures with infill masonry panels. These buildings offered insufficient capacity, lacked ductile detailing and were poorly constructed and may have limited durability.

RC building typologies | DAMAGE ASSESSMENT

RC Buildings

WDS (Well Designed Structure)	WDS building structures designed based on the International standards/codes (e.g. Indian Standard code), considering seismic design with ductile detailing
NBC (MRT) (Nepal Building Code)	NBC structures are designed with MRT, which provides some ready-to-use provisions in terms of dimensions and details for structural and non-structural elements for up to 3 storeys in RC framed, ordinary residential buildings in Nepal
NBC+ (MRT) (Modified Nepal Building Code)	NBC+ is an improvement of the recommendations for the minimum size and reinforcement detailing in columns, relatively to the NBC.
CCP (Current Construction Practices)	Buildings group that represent the CPP in Nepal, structures in many urban areas of Nepal represent the largest group.

RC building typologies | DAMAGE ASSESSMENT



Buildings with infill walls | DAMAGE ASSESSMENT

Deficient RC structural systems | Solid brick infill walls with poor mortar

Buildings with infill walls | Damage Assessment

Poor quality of materials and construction detailing

Buildings with infill walls | DAMAGE ASSESSMENT

Soft-storey mechanisms | Elevation irregularity | Failure of columns

Buildings with infill walls | DAMAGE ASSESSMENT

Soft-storey mechanisms | Elevation irregularities | 3+ Added storeys

Buildings with infill walls | DAMAGE ASSESSMENT




Columns/Joints shear failure | Poor detailing | Inadequate bars anchorage and insufficient stirrups | Poor materials quality

Buildings with infill walls | DAMAGE ASSESSMENT

Medium-rise buildings | Severe damages concentrated in some columns at ground level | In-plan irregularity (only-one full infilled façade)

Buildings with infill walls | DAMAGE ASSESSMENT

Medium-rise buildings | Poor quality of concrete | Shear-out

Buildings with infill walls | DAMAGE ASSESSMENT

Medium-rise building | Severe damages concentrated in some columns at ground level | In-plan irregularity (only-one full infilled façade)

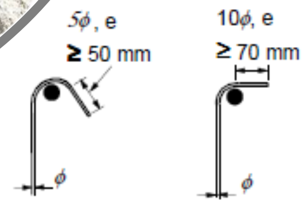
Buildings with infill walls | DAMAGE ASSESSMENT

Medium-rise building | Strong infill walls | Shear sliding mechanism and damage in adjacent columns (shear-out)

Buildings with infill walls | DAMAGE ASSESSMENT

Inadequate capacity of Columns | Dimensions and detailing | Soft-storey

Buildings with infill walls | DAMAGE ASSESSMENT



Insufficient capacity of RC elements | Dimensions and detailing

Soft-storey | Stirrups failure

Buildings with infill walls | Damage Assessment

High-rise WDS buildings

Damages essentially at non-structural elements

Buildings with infill walls | DAMAGE ASSESSMENT

High-rise WDS buildings

Pronounced in-plane cracking | Out-of-plane collapse of walls

Remarks on the mission | DAMAGE ASSESSMENT

Non-designed structures suffered extensive damage

Partial or full collapses, mostly due to vertical irregularities

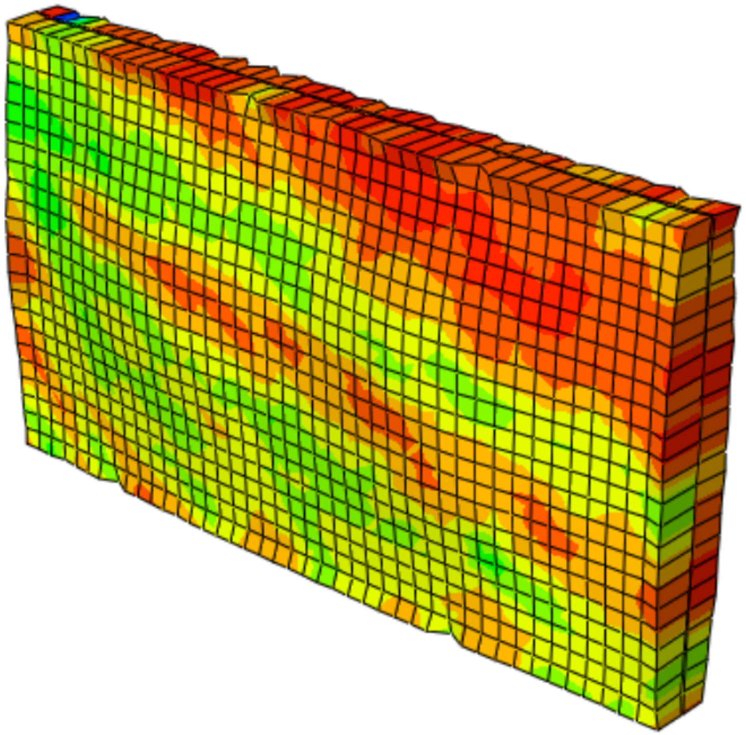
Well-designed RC buildings demonstrated significant non-structural damage

Insufficient control by Nepalese entities (design and construction)

Numerical developments

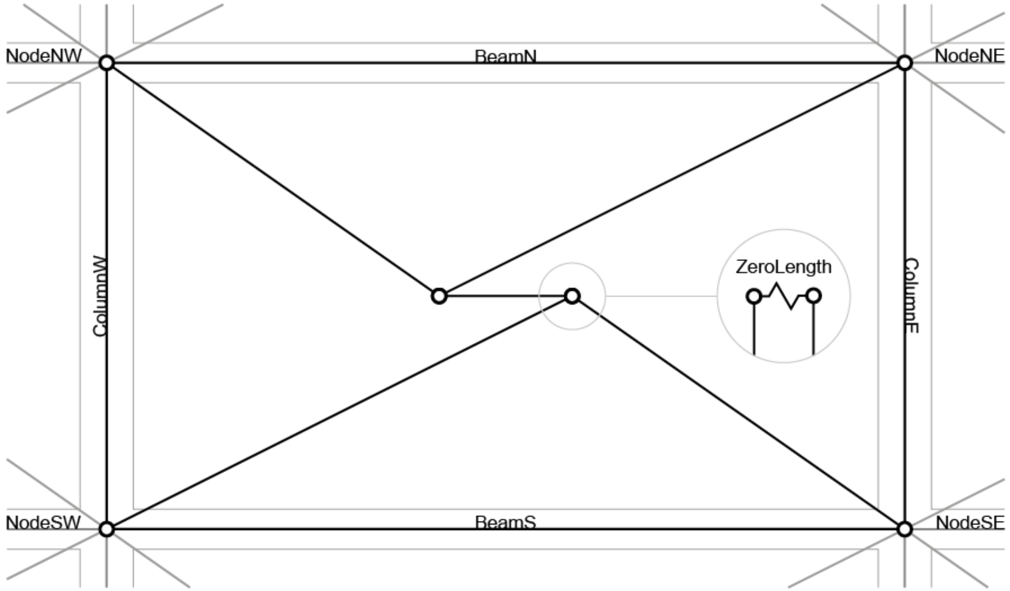
Semi-refined modelling

Abaqus – Parametric study



Macro modelling

OpenSees – New element



Semi-refined | Numerical modelling

Volume elements

Continuum element for infill wall

Study:

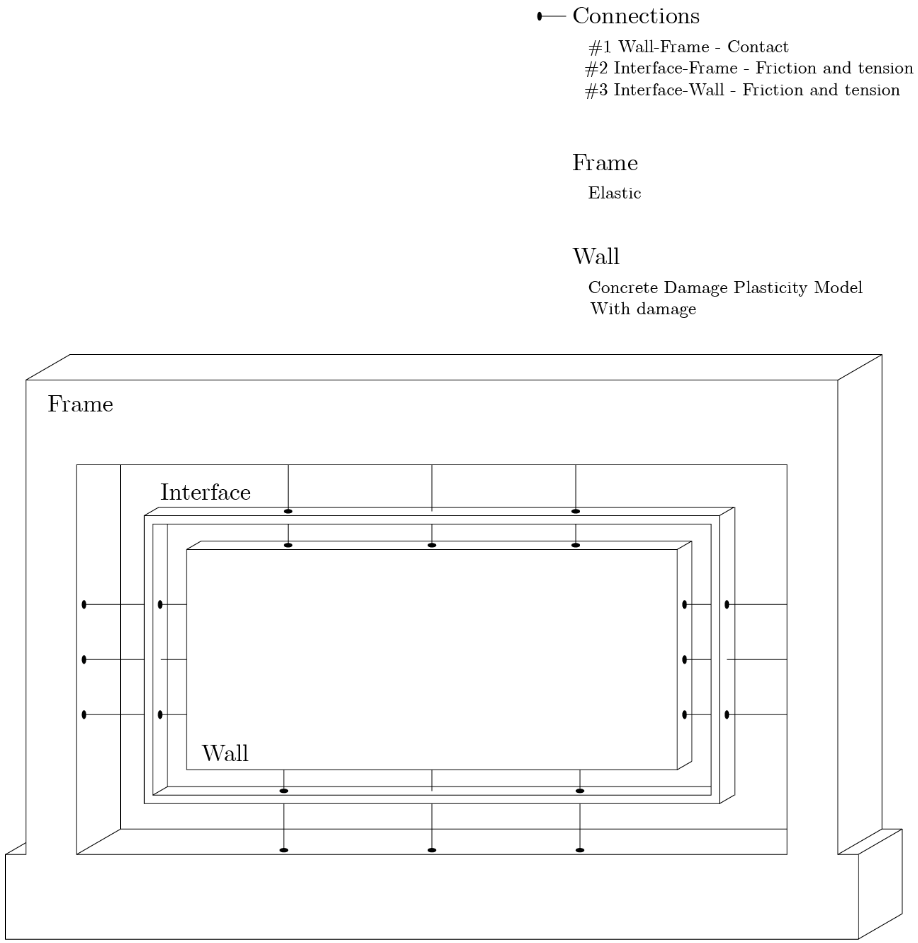
Dimensions

Properties of materials

Infill-frame interface conditions

Eccentricities

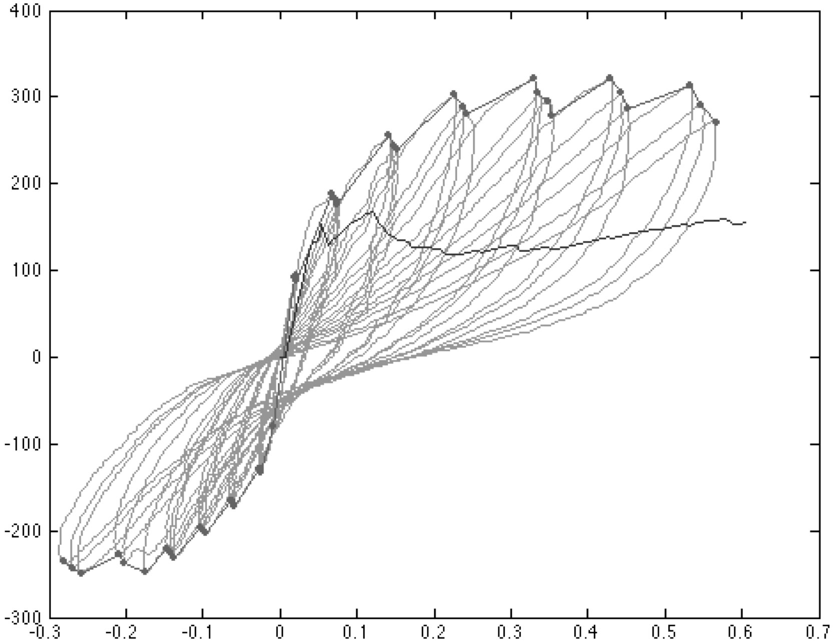
Single- and double-leaf walls

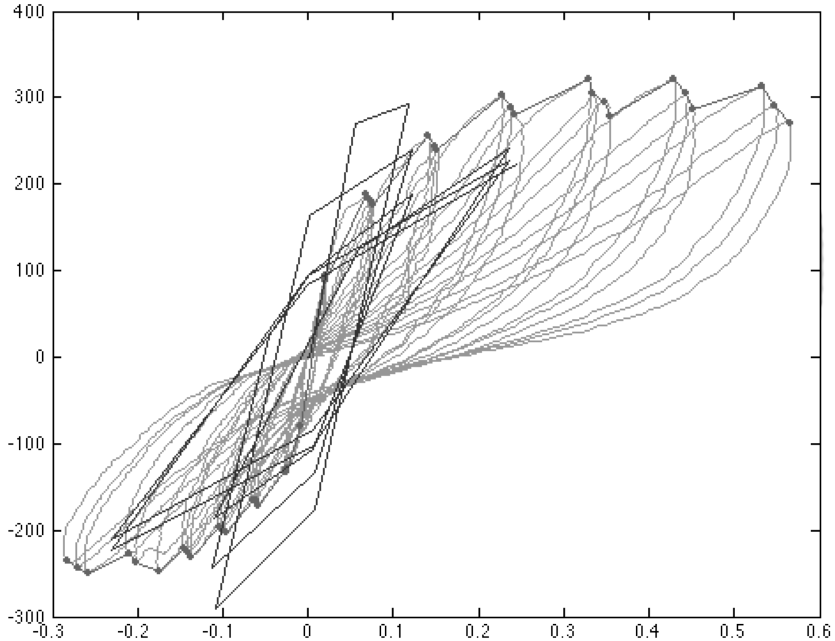


Semi-refined | Numerical modelling

Boundary connections with different strategies

Pushover and cyclic analysis

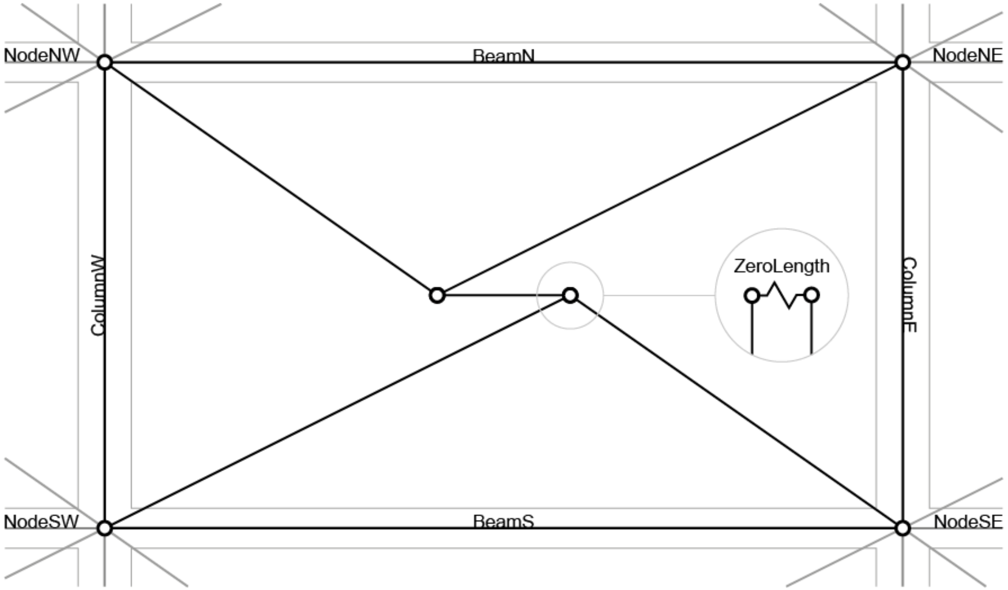




Infill macro-model | Numerical modelling

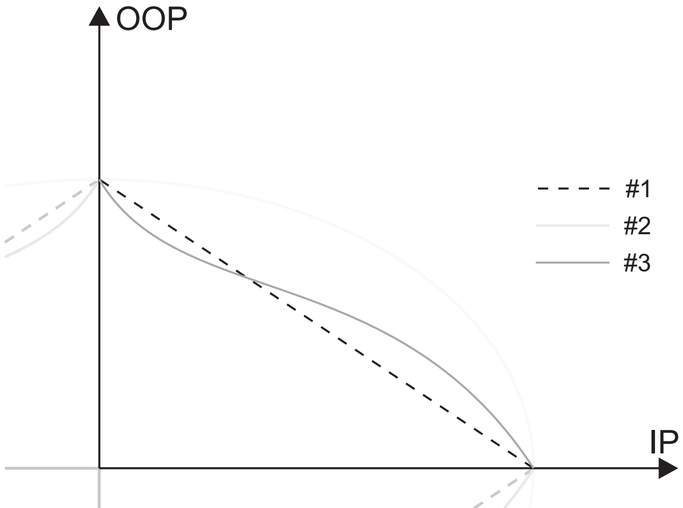
Out-of-plane behaviour

Interaction between two masonry walls and its connections



Simplified approach for assessment of failure's strength for actions combined in both directions: in-plane and out-of-plane

Applicability on the simulation of real (and complex) study cases



Infill macro-model #1 | Numerical modelling

Example using the default elements provided by OpenSees

```
geomTransf Linear $transfTag $vecxzX $vecxzY $vecxzZ
node $nodeTag (ndm $coords) <-mass (ndf $massValues)>
    node …
equalDOF $rNodeTag $cNodeTag $dof1 $dof2
    equalDOF …
uniaxialMaterial (material) $matTag …
    uniaxialMaterial …
element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz $transfTag
    element …
    element …
    element …
    element …
recorder Collapse …
    recorder Collapse …
    recorder Collapse …
```

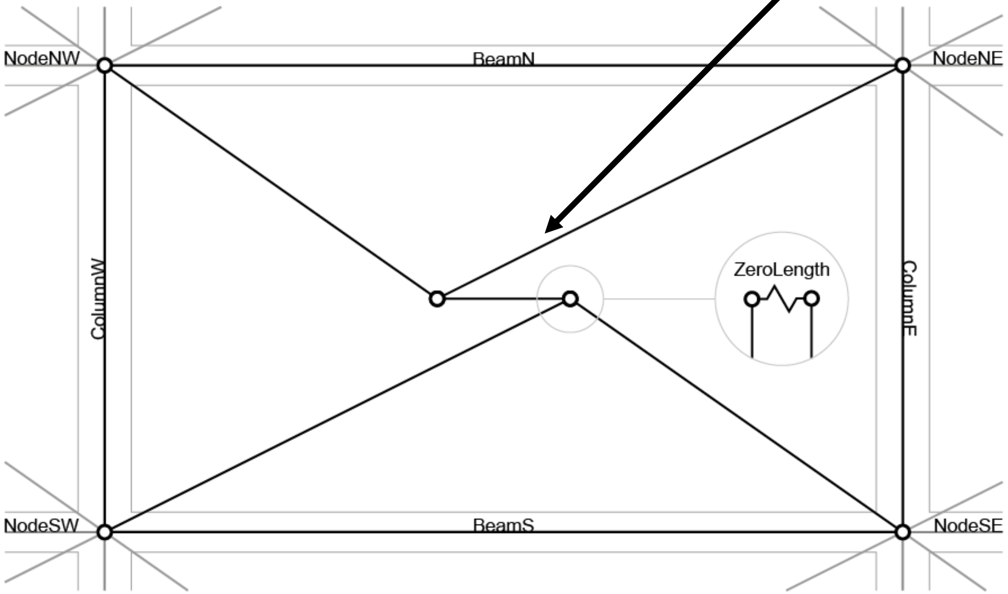
Infill macro-model #2 | Numerical modelling

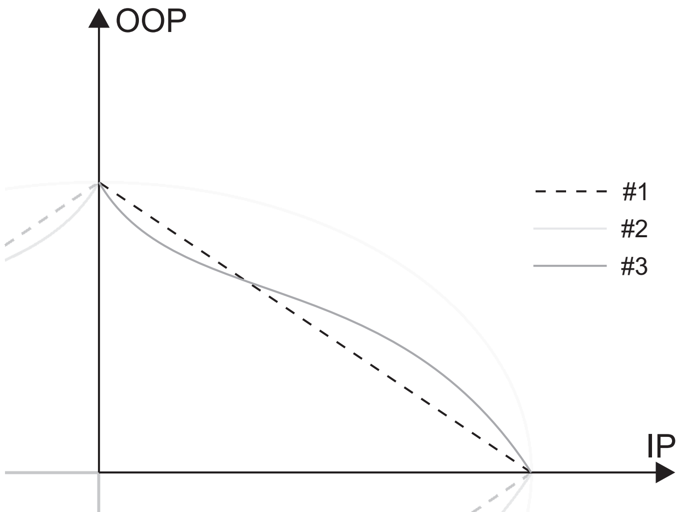
Using new element of OpenSees

uniaxialMaterial (material) $matTag …

uniaxialMaterial …

element InfillWall $eleTag $n1 $n2 $n3 $n4 $nc1 $nc2 $A $matElast $matInelas -fileInfill $failurecurve -mass $mass





Infill macro-model #2 | Numerical modelling

Structural model in TCL

ex4d.tcl

File Path : ~/bin/ex4d.tcl

ex4d.tcl (no symbol selected)

```
set infillcode 1;
#element Truss2D 9 1 8 $Astrut $matBrickTagElast;
#element Truss2D 10 4 5 $Astrut $matBrickTagElast;
if {$infillcode == 1 } {

#element InfillWall 9 1 2 3 4 9 10 $Astrut $matBrickTagElast $matBrickTagInelas -rho 1;
#element InfillWall 10 5 6 7 8 11 12 $Astrut $matBrickTagElast $matBrickTagInelas -rho 1;
#element InfillWall 11 5 1 4 8 13 14 $Astrut $matBrickTagElast $matBrickTagInelas -rho 1;
#element InfillWall 12 6 2 3 7 15 16 $Astrut $matBrickTagElast $matBrickTagInelas -rho 1;

set failurecurve "FailureIPandOOP.tcl";

#element InfillWall 9 5 1 4 8 9 10 $Astrut $matBrickTagElast $matBrickTagInelas -fileInfill $failurecurve;
element InfillWall 9 5 1 4 8 9 10 $Astrut $matBrickTagElast $matBrickTagInelas;
element InfillWall 10 1 2 3 4 11 12 $Astrut $matBrickTagElast $matBrickTagInelas;
element InfillWall 11 5 6 7 8 13 14 $Astrut $matBrickTagElast $matBrickTagInelas;
#element InfillWall 12 6 2 3 7 15 16 $Astrut $matBrickTagElast $matBrickTagInelas;
element InfillWall 12 6 2 3 7 15 16 $Astrut $matBrickTagElast $matBrickTagInelas -fileInfill $failurecurve;

#set mass 1;

#mass 9 $mass $mass 0. 0. 0. 0.;
#mass 10 $mass $mass 0. 0. 0. 0.;
#mass 11 $mass $mass 0. 0. 0. 0.;
#mass 12 $mass $mass 0. 0. 0. 0.;
#mass 13 $mass $mass 0. 0. 0. 0.;
#mass 14 $mass $mass 0. 0. 0. 0.;
#mass 15 $mass $mass 0. 0. 0. 0.;
#mass 16 $mass $mass 0. 0. 0. 0.;

} elseif {$infillcode == 2} {
    node 5 1.75 1.5;
    node 6 2.75 1.5;

    element elasticBeamColumn 4 1 6 $Ac $Ec $Ic $transfTag;
    element elasticBeamColumn 5 6 2 $Ac $Ec $Ic $transfTag;
    element elasticBeamColumn 6 5 3 $Ac $Ec $Ic $transfTag;
    element elasticBeamColumn 7 4 5 $Ac $Ec $Ic $transfTag;
    element elasticBeamColumn 8 5 6 $Ac $Ec $Ic $transfTag;
```

Infill macro-model #2 | Numerical modelling

Structural model in TCL

API Element

InfillWall.h

File Path : ~/Desktop/OPSMakeAPI/element/cpp/InfillWall.h

InfillWall.h class InfillWall

```
/* ****************************************************************** **
**    OpenSees - Open System for Earthquake Engineering Simulation    **
**          Pacific Earthquake Engineering Research Center            **
**                                                                    **
**                                                                    **
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**                                                                    **
** Developed by:                                                      **
**   Frank McKenna (fmckenna@ce.berkeley.edu)                         **
**   Gregory L. Fenves (fenves@ce.berkeley.edu)                       **
**   Filip C. Filippou (filippou@ce.berkeley.edu)                     **
**                                                                    **
** ****************************************************************** */

// $Revision: 0.1 $
// $Date: 2015 $
// $Source:  $
// $Base
// $URL: svn://opensees.berkeley.edu/usr/local/svn/OpenSees/trunk/SRC/element/tr

#ifndef InfillWall_h
#define InfillWall_h

// Written: JDO, HV
// Description: This file contains the interface for the InfillWall class.

#include <Element.h>
#include <Matrix.h>
#include <Vector.h>
```

InfillWall.cpp

File Path : ~/Desktop/OPSMakeAPI/element/cpp/InfillWall.cpp

InfillWall.cpp InfillWall::InfillCollapse

```
/* ****************************************************************** **
**    OpenSees - Open System for Earthquake Engineering Simulation    **
**          Pacific Earthquake Engineering Research Center            **
**                                                                    **
**                                                                    **
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**   Filip C. Filippou (filippou@ce.berkeley.edu)                     **
**                                                                    **
** ****************************************************************** */

// Written: JDO, HV
// Created: 2015
// Revised: December 2015
//
// Based on Truss.cpp
// Help:
//      by Arash    /OpenSees/SRC/element/joint/Joint2D.cpp
//      by MRL      /OpenSees/PACKAGES/NewElement/cpp/RotationShearCurve.cpp
//      by fmk      /OpenSees/SRC/domain/constraints/RigidBeam.cpp
//
// Description: This file contains the implementation for the InfillWall class.

// Header files
#include "InfillWall.h"
#include <elementAPI.h>
#include <G3Globals.h>

#include <Information.h>
#include <Domain.h>
#include <Node.h>
```

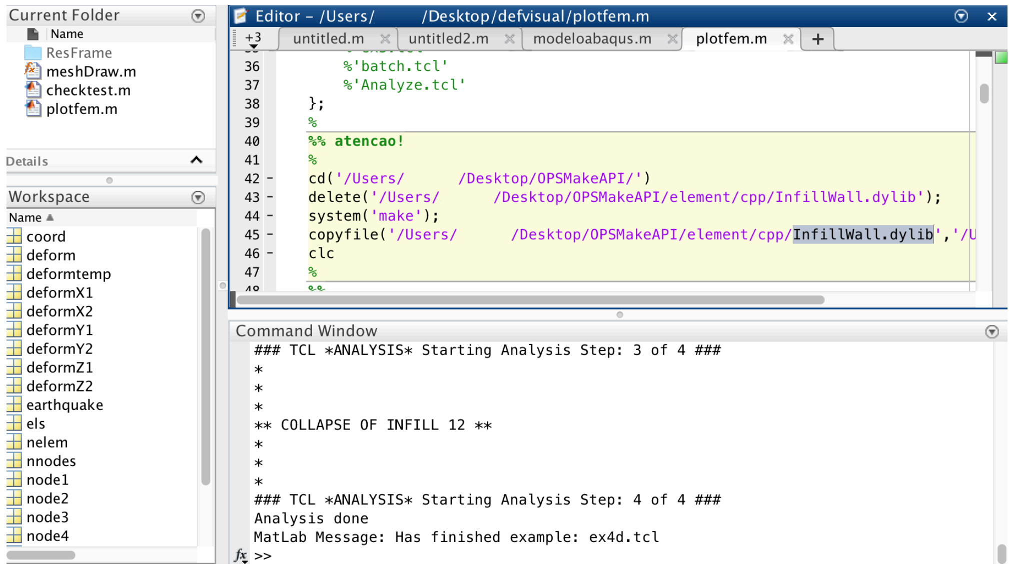
Infill macro-model #2 | Numerical modelling

Structural model in TCL

API element in C++

Matlab

- Compile element
- Run model with OpenSees
- (Warnings on Command window)
- (Results on Workspace)



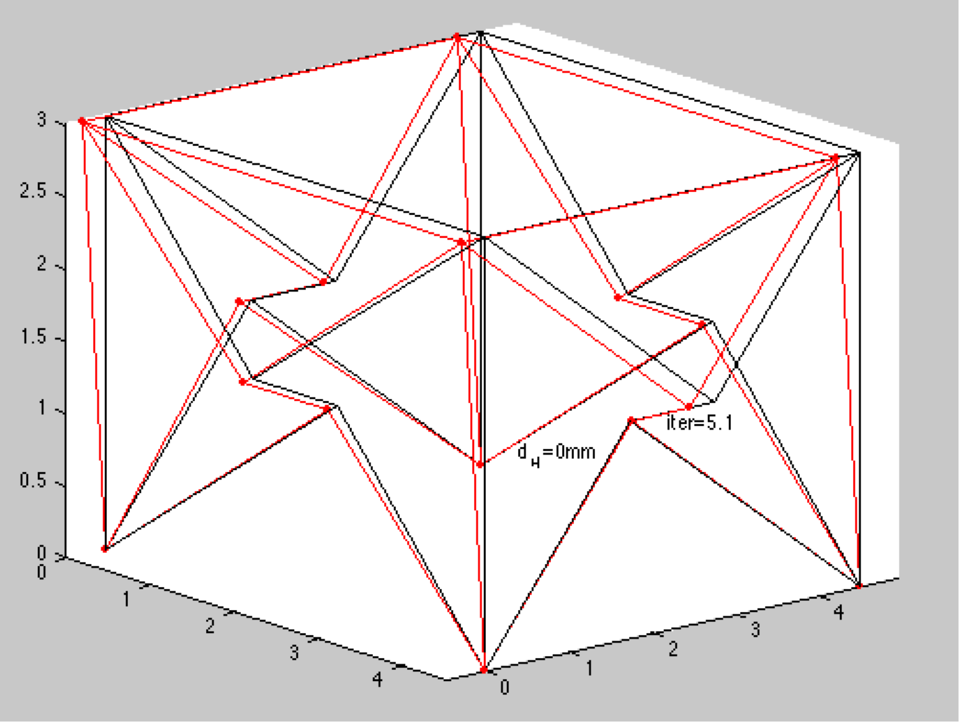
Infill macro-model #2 | Numerical modelling

Structural model in TCL

API element in C++

Matlab

- Compile element
- Run model with OpenSees
- (Warnings on Command window)
- (Results on Workspace)
- Post-Processor



Developments

Complete the development of the new element for OpenSees, by correcting errors and bugs.

Calibration and validation of models with experimental data collected from previous testing campaigns developed at FEUP-LESE, and other available data.

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