# *Development and Validation of a Resilient Hybrid Bracing System for Seismic Hazards*

**Monique Head, PhD & Mehdi Shokouhian, PhD**
**http://moniquehead.com**
Associate Professor, Structural Engineering
Department of Civil Engineering
Morgan State University

***December 5, 2016***

**RESEARCHERS WORKSHOP: ADVANCED SIMULATION FOR NATURAL HAZARDS MITIGATION**

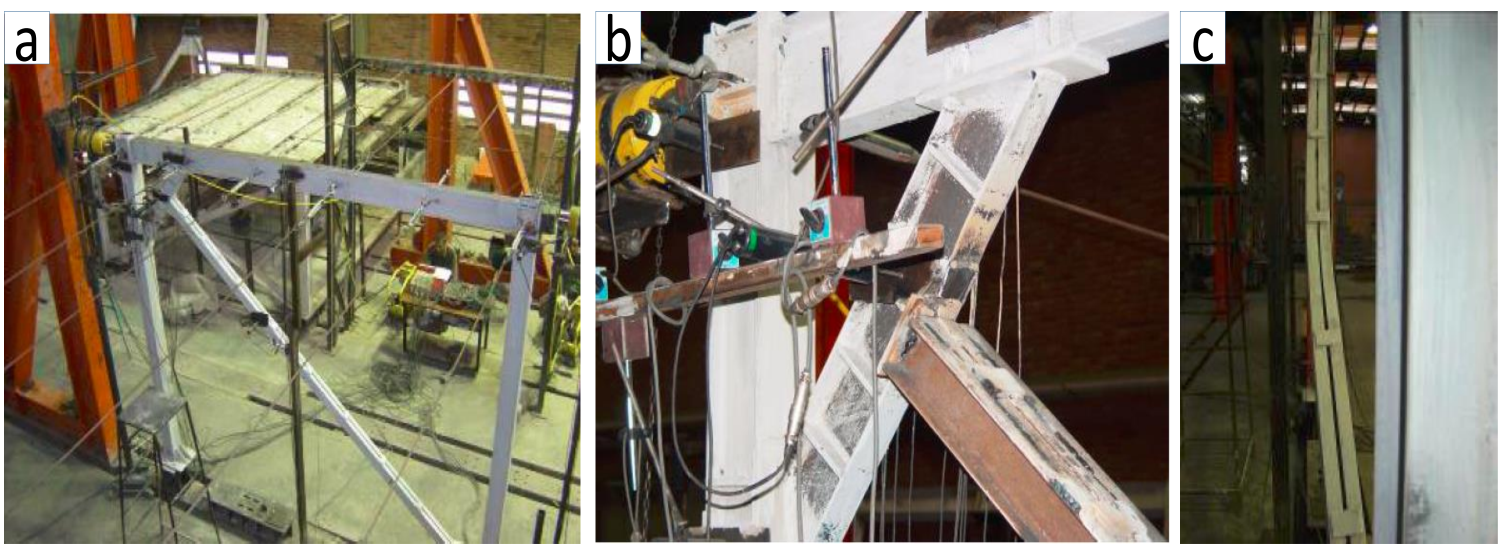
MORGAN STATE UNIVERSITY

# OUTLINE

- Background
- Concept of BRKBF
- Objective
- Preliminary Results
- Proposed Work Plan for Experimental Testing
- Expected Outcomes


# BACKGROUND

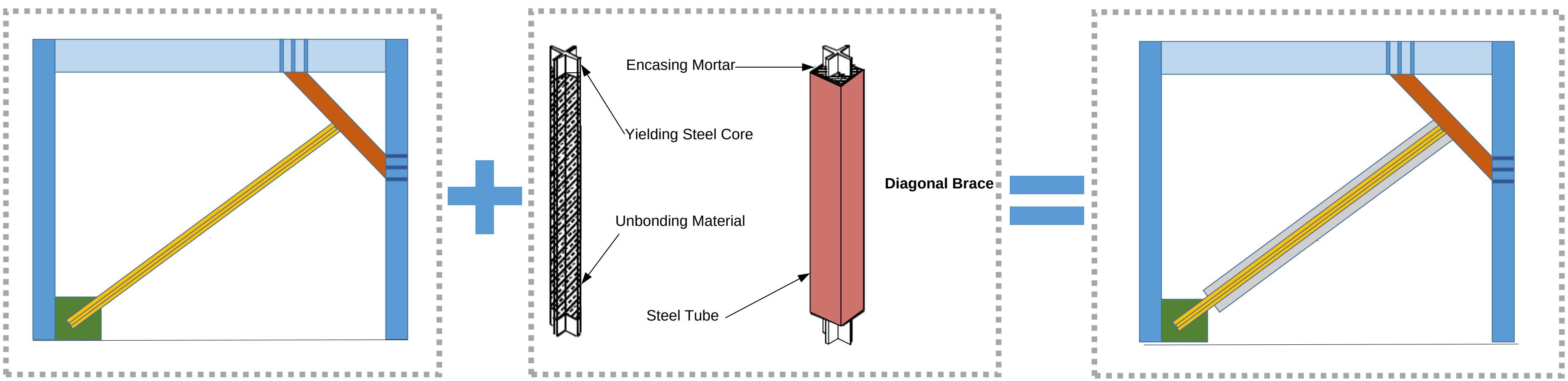
- Aristizabal-Ochoa (1986) proposed a framing system that combined the stiffness of a diagonal brace with the ductile behavior of a knee element--KBF.
- However, ***not suitable*** for earthquake-resistant design since brace was designed to be ***slender***. Consequently, the brace buckled and lead to pinching of the hysteresis, which is not efficient for energy dissipation. Inelastic cyclic deformations of the brace which buckles may create a lateral instability problem at the knee-brace joint and cause a sudden change to the restoring force of the structure.
- The inelastic response of a KBF system under cyclic loading reversals is characterized by ***significant degradation of the brace compression resistance and stiffness, permanent brace deformation, and, eventually, local buckling and fracture at plastic hinge locations***.




Experimental investigation of KBF conducted by Zahrai. M in 2014, (a) specimen and test setup, (b) Termination of KBF1 test by fracture of knee-diagonal brace weld at KBF1 test specimen, (c) overall buckling of diagonal brace

# CONCEPT OF BRKBF

The **BRKBF** consists of BRBs within a KBF to eliminate the buckling failure mode of the diagonal member in addition to using low strength steel so that the *knee element can dissipate more energy before failure*. This enhanced passive damping system, combining KBFs and BRBs, results in an optimized structural system whereby the full capacity of steel members and smaller member sizes for the diagonal members is designed and can offer low cost, high ductility, and limit damage to the small knee element as an energy dissipater.




**KBF** **BRB** **BRKBF**

# OBJECTIVE

- The ***research objective*** is to develop a ***new integrated structural system*** referred to as a **Buckling Restrained Knee Braced Frame (BRKBF)** system that takes existing technology and uses it in a manner that has never been done before that outperforms and exceeds the seismic performance of existing concepts for structural framing systems.

We anticipate that the **proposed hybrid structural system (BRKBF) will improve energy dissipation of the overall system, while resisting severe earthquakes.**

# PRELIMINARY MODELING - OpenSees

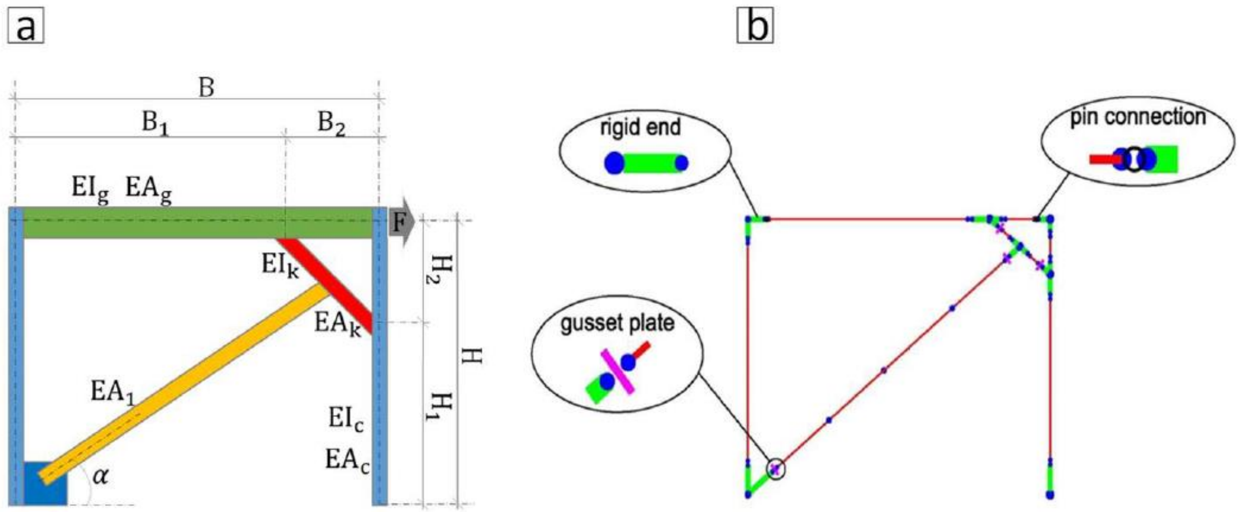



**Figure 1.** Structural model and dimensions: (a) Basic parameters of knee braced frame, (b) Frame member connections in Opensees model

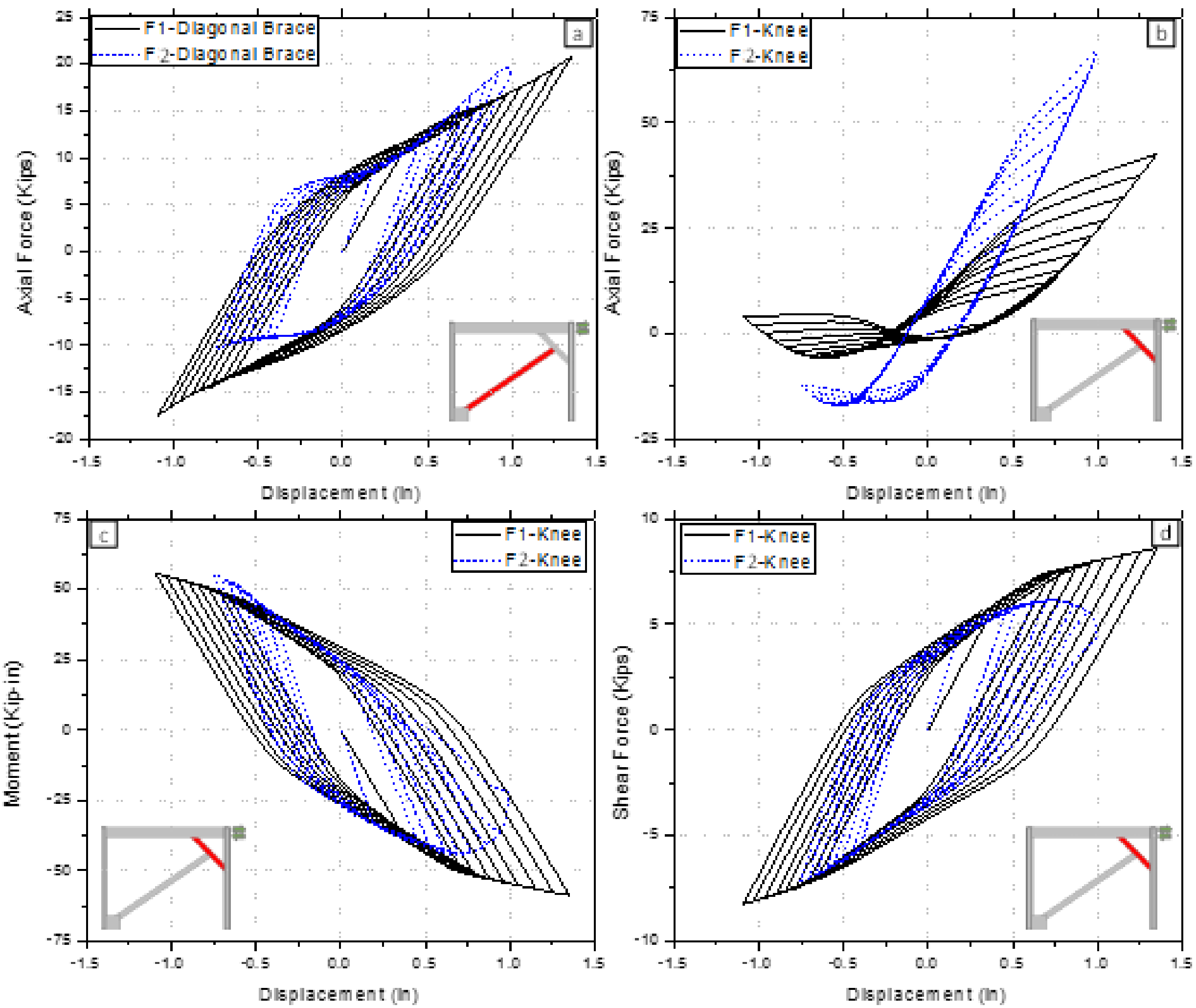
**Table 3**. Frame sections and material

| | Frame 1 | | Frame 2 | |
|---|---|---|---|---|
| **Member** | **Section** | **Material** | **Section** | **Material** |
| Columns | H150 × 150 × 10 | St37(A36) | H185 × 185 × 12 | St37(A36) |
| Beam | I150 × 120 × 10 | St37(A36) | I210 × 150 × 12 | St37(A36) |
| Diagonal member | H100 × 100 × 8 | St37(A36) | H120 × 120 × 12 | St37(A36) |
| Knee member | I150 × 120 × 10 | St37(A36) or St12 (A366) | I210 × 150 × 12 | St37 (A36) or St12 (A366) |

# PRELIMINARY RESULTS

Cyclic response of the KBF modeled using **OpenSees** 2.4.0 was employed and ATC-24 loading protocol was applied to evaluate the cyclic response of frames with different design parameters.

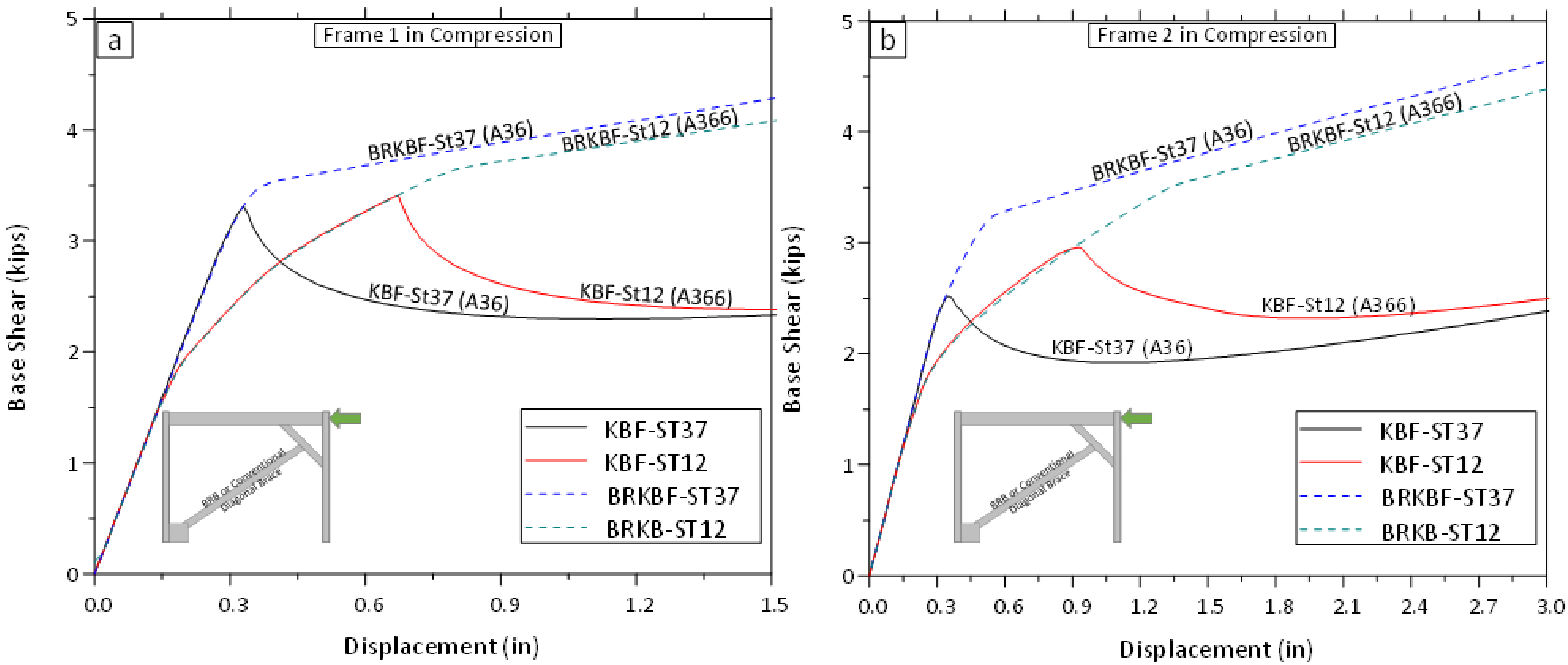
Results reveal that there is a 16% difference between tension and compression forces at the last cycle for Frame 1, while Frame 2 shows 48% difference. This difference is due to buckling of diagonal brace that causes premature collapse in the frame and prevents the knee element from functioning as structural fuse.




Cyclic analyses of KBF: (a) Cyclic response of diagonal brace in axial force, (b) Cyclic response of knee element in axial force, (c) Cyclic response of knee element in bending moment, (d) Cyclic response of knee element in shear force.

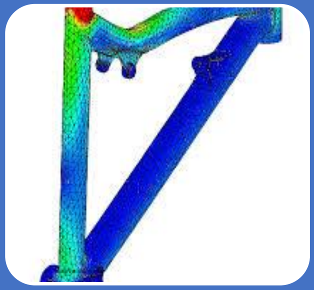
# PRELIMINARY RESULTS – pushover response

- Results show an enhanced performance of BRKBF compared with KBF due to prevention of the buckling of the diagonal brace member
- Resiliency of system can be improved by reducing probability of failure during earthquake. It can be seen that a higher base shear and displacement can be obtained for BRKBF.




Comparison between pushover response of KBF and BRKBF in compression, (a) Frame 1 with ST37 (A36) and ST12 (A366), (b) Frame 2 with ST37 (A36) and ST 12

# PROPOSED WORK PLAN



## PHASE I: Analytical Modeling of BRKBF Structural System

Development of Prototype Structure

Performance-Based Design Procedure

Numerical Studies

## PHASE II: 2D and 3D Experimental Investigation

2D BRKBF Full-scale Cyclic Testing and Hybrid Simulation @NHERI Lehigh Facility

3D BRKBF Half-scale Shake Table Testing @Morgan State University

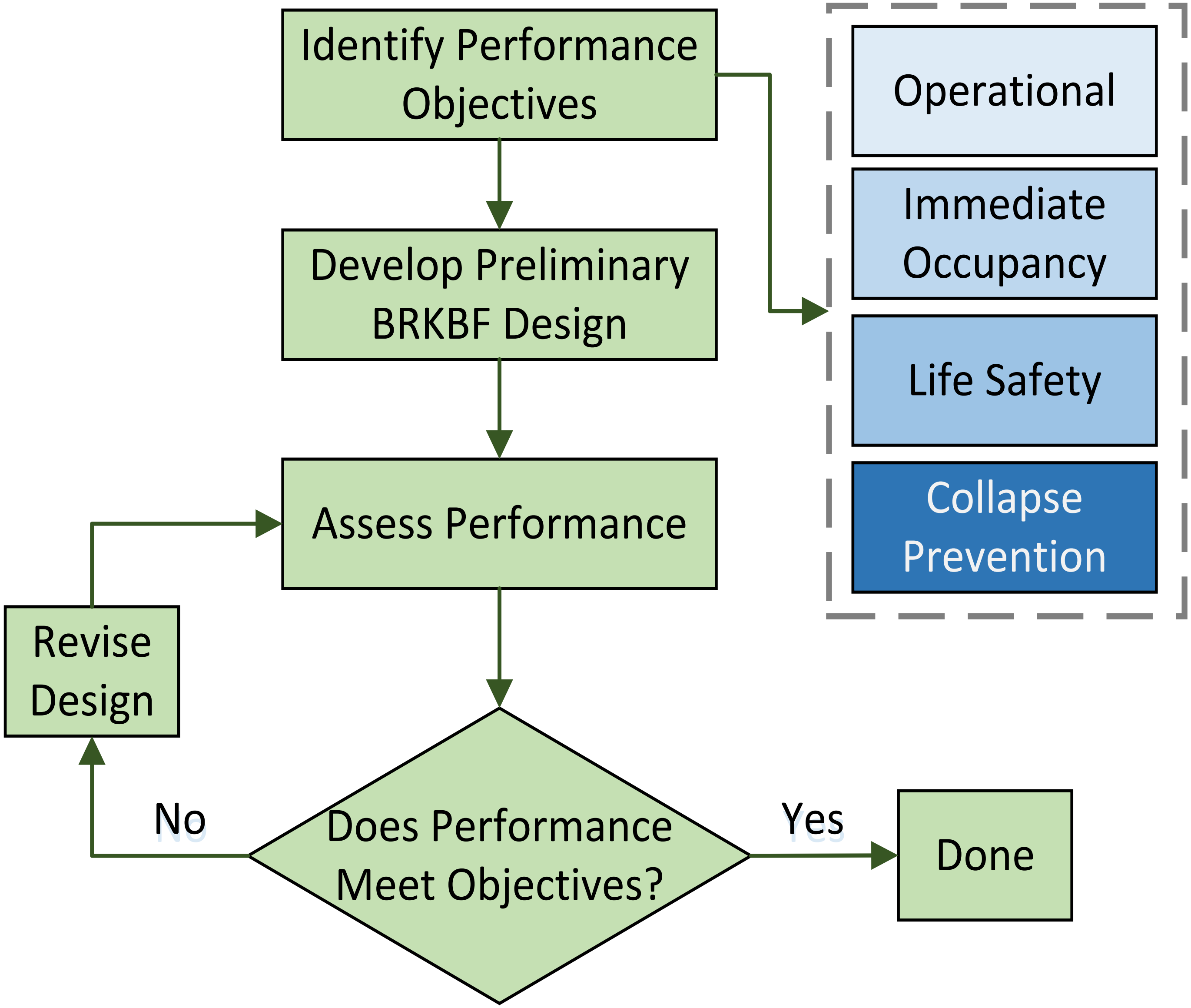
## PHASE III: Validation of BRKBF Structural System

Calibration of Numerical Models

Parametric Numerical Study of Prototype Structure

Seismic Design Recommendations

# PERFORMANCE-BASED DESIGN



# PROPOSED WORK FLOW

## Collaborative Research: Development and Validation of a Resilient Hybrid Bracing System for Seismic Hazards

**Morgan State University**

- Dr. Monique Head (MSU-PI)
- Dr. Mehdi Shokouhian (MSU Co-PI)
- Consultant
- Lab Technician
- 1 Graduate Student

**Lehigh University**

- Dr. James Ricles (LU-PI)
- 1 Graduate Student
- Lab Technicians

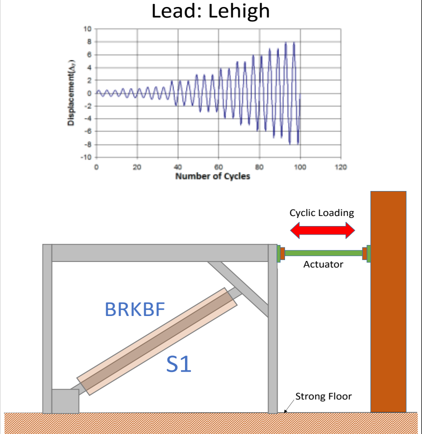
**Task 1**
Development of Prototype Structure
Lead: MSU/Lehigh

**Task 2**
Development of Performance-Based Design Procedure
Lead: MSU/Lehigh

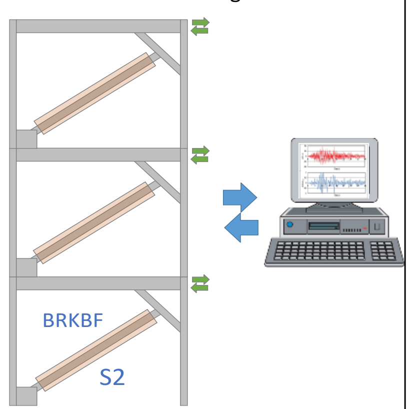
**Task 3**
Preliminary Numerical Study
Lead: MSU/Lehigh

**Task 4**
2D and 3D Experimental Investigation
Lead: Lehigh/MSU

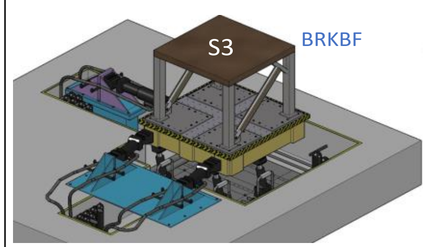
**Subtask 4.1**
Full-Scale Cyclic Displacement Testing
Specimen 1: 2D, 1-Story, 1-Bay, BRKBF (S1)
Lead: Lehigh




**Subtask 4.2**
Full-Scale Hybrid Simulation Testing
Specimen 2: 2D, 3-Story, 1-Bay, BRKBF (S2)
Lead: Lehigh




**Subtask 4.3**
6DOF Shake Table Testing
Specimen 3: 3D, 1-Story, 1-Bay, BRKBF (S3)
Lead: MSU




**Task 5**
Calibration of Numerical Models
Lead: MSU/Lehigh

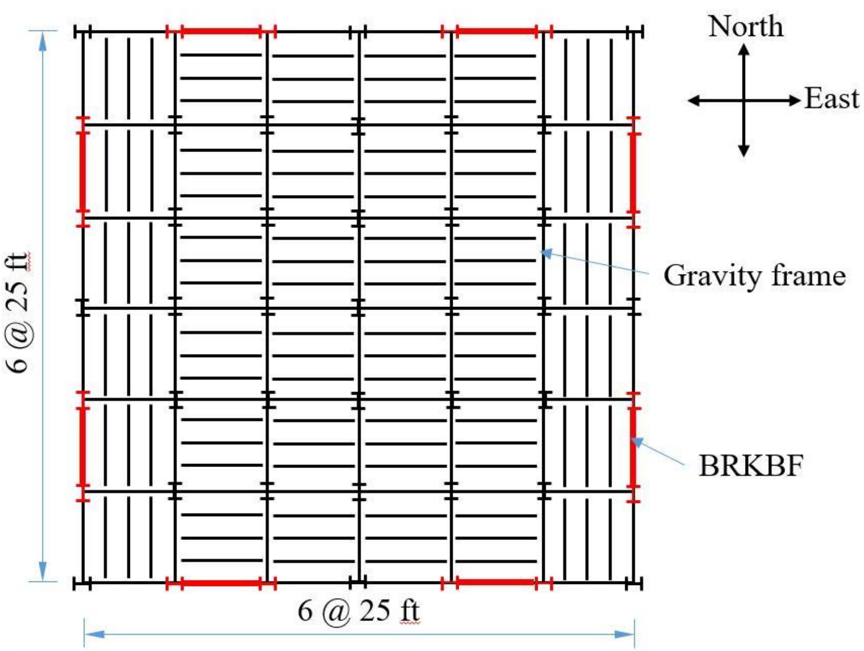
**Task 6**
Parametric Numerical Study of Prototype Structure
Lead: MSU

**Task 7**
Assessment of Performance-based Design Procedure
Lead: MSU/Lehigh

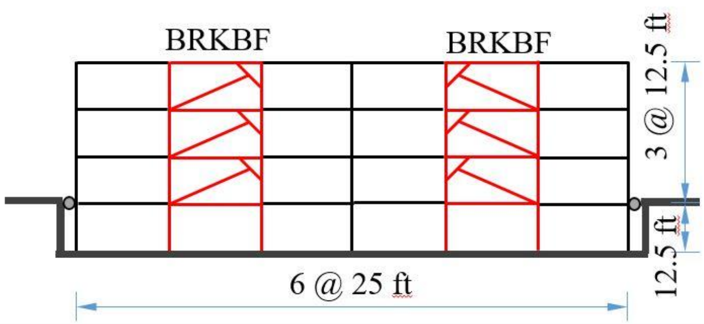
**Task 8**
ECO
Lead: MSU/Lehigh

# PROPOSED LAYOUT FOR TESTING

A hybrid real-time simulation of a full-scale, two-dimensional, three-story, single bay BRKBF designated as Specimen S2, which is planned to be manufactured, instrumented and tested under a cyclic loading at Lehigh University.



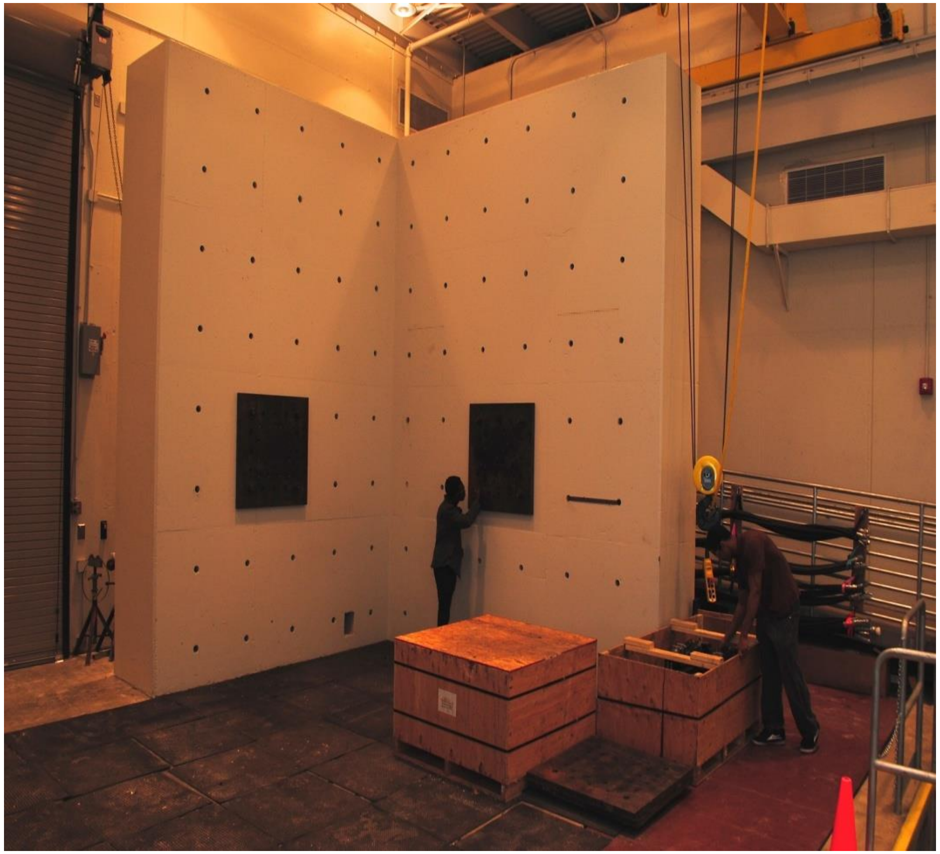

A mockup and placement (plan and elevation view) of the prototype structure for which the BRKBF is extracted for the test program, including hybrid simulations, at the Lehigh NHERI Experimental Facility




| Specimen | Description | Dimensions | Method | Objectives |
|---|---|---|---|---|
| **S1** | 2D Full-scale BRKBF | L=5m, H=3.4m | Cyclic displacement testing | Results will be used for detailing design of S2, and developing a baseline to assess S2 and S3 tests |
| **S2** | 2D Full-scale BRKBF | L=5m, H=10.2m | Hybrid simulation testing | Extending the results of S1 for multi-story BRKBF to ensure resiliency of the system |
| **S3** | 3D Half-scale BRKBF | L=2.5, W=2.5, H=1.7m | 6DOF shake table testing | Performance assessment of BRKBF at system-level |

# CBEIS – Center for the Built Environment and Infrastructure Studies

# New Large-Scale Structural Testing Facilities at Morgan State University



**L-shaped Strong Wall-Strong Floor**
**CBEIS 121**

**6DOF Seismic Simulator**
**CBEIS 121**

6DOF Seismic Simulator with Water Cooler

# Thank you!

**Monique Head, PhD**
monique.head@morgan.edu
Website: http://moniquehead.com
Associate Professor, Structural Engineering
Department of Civil Engineering
Morgan State University
Baltimore, MD 21251-0001
USA