



# Structural Health Monitoring using Acceleration Data and Machine Learning Techniques

Sifat Muin and Khalid M. Mosalam

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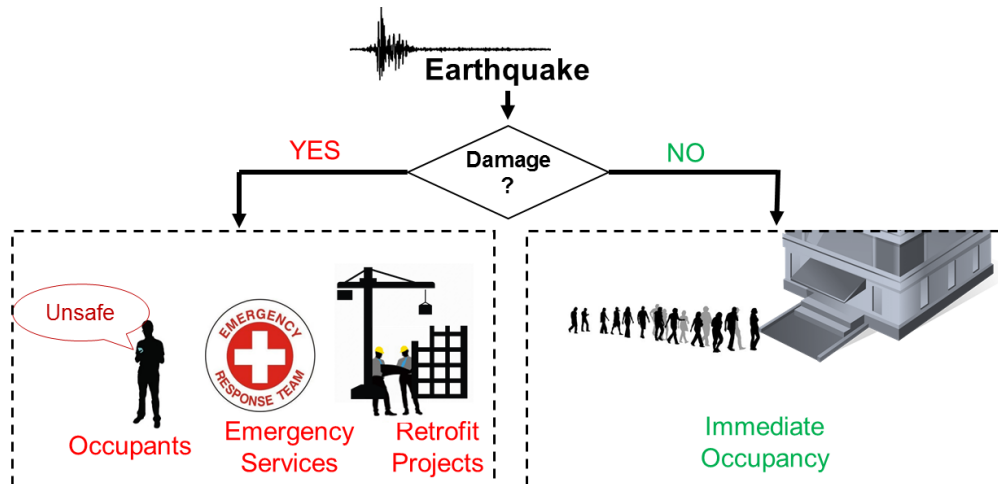
# Outline

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- Motivation and SHM background
  - CAV as a damage feature
  - CAV in Machine Learning
  - H-MC Framework for SHM
    - Conclusion

# Motivation

- Current US infrastructure systems need continuous monitoring.

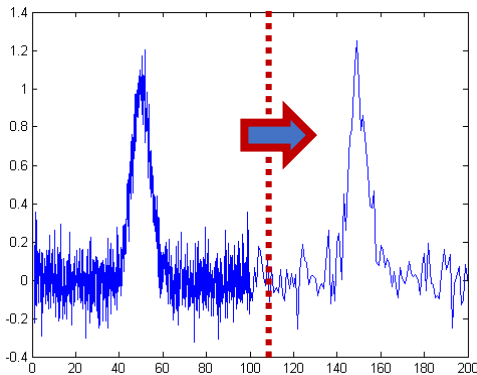
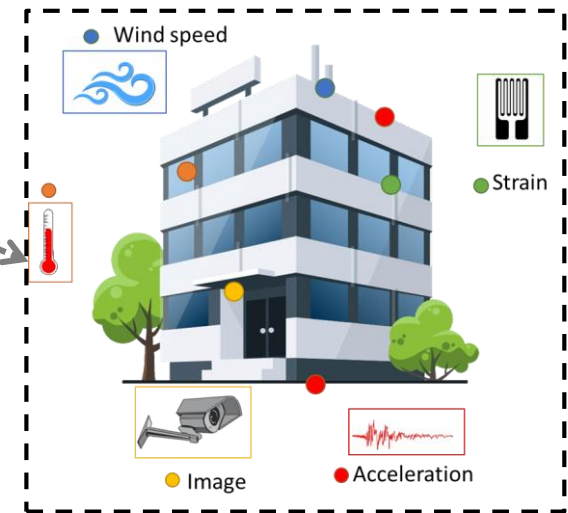
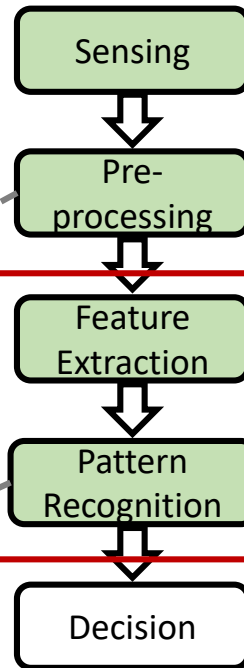


Knowledge about damage → Decision:  
1. Damage → plan proper response.  
2. No damage → immediate occupancy.

# SHM Process

SHM is the process to develop online damage detection and/or assessment capability for engineered systems (aerospace, **civil**, mechanical).

## Processing chain of SHM



PGA, Drift, Power Spectra, IRF, **CAV**, etc.

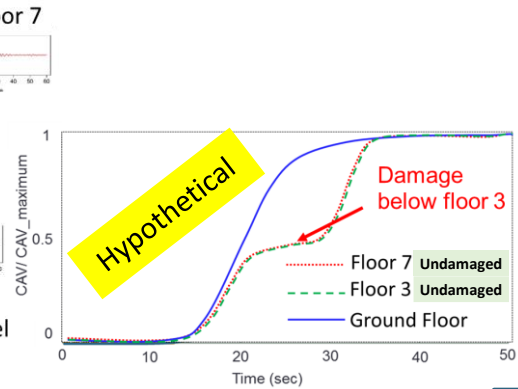
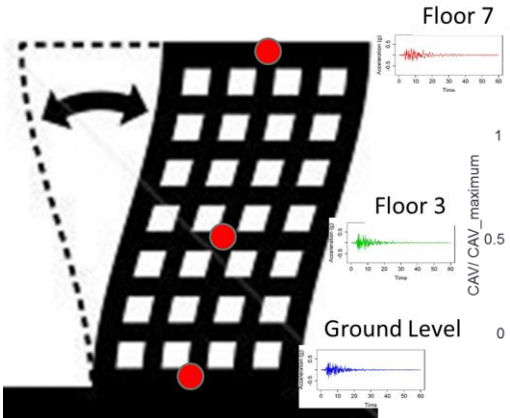
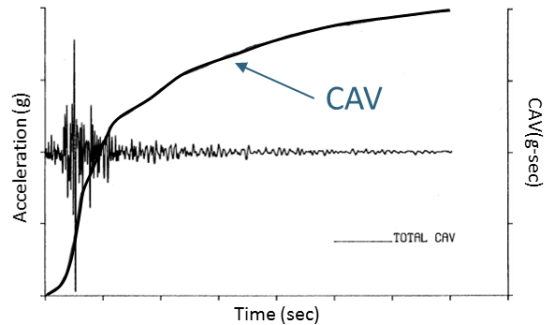
**CAV: Cumulative Absolute Velocity**

In this study, Machine Learning (ML)

# CAV & Damage

## CAV: Cumulative Absolute Velocity

$$CAV = \int_0^T |\ddot{u}(t)| dt$$



### Bridge column shaking table test

**Sensor location**

- 3D Accelerometer
- 1D Accelerometer (Z)

**Column cross section**

**Ground motion 125% scale**

Scale	Crack propagation	CAV Plots	NCAV plots
25% Undamaged	No visible cracks	CAV with linear trend	Closely packed NCAV
50% Yield level	Flexural cracks appear at top & bottom	Massblock CAV value is lower than columntop	Massblock NCAV shows deviation
125% Damaged	Flexural and shear cracks, Spalling at top	Excitation barely reaching massblock	Large deviation in massblock NCAV

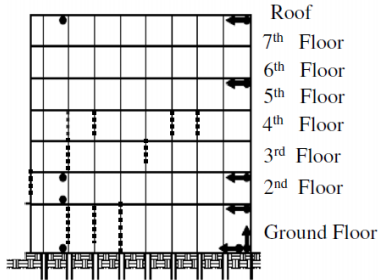
East end column line  
Source: <http://www.construction.com/resources/reports/>

Only sensor to sensor deviation identified damaged side

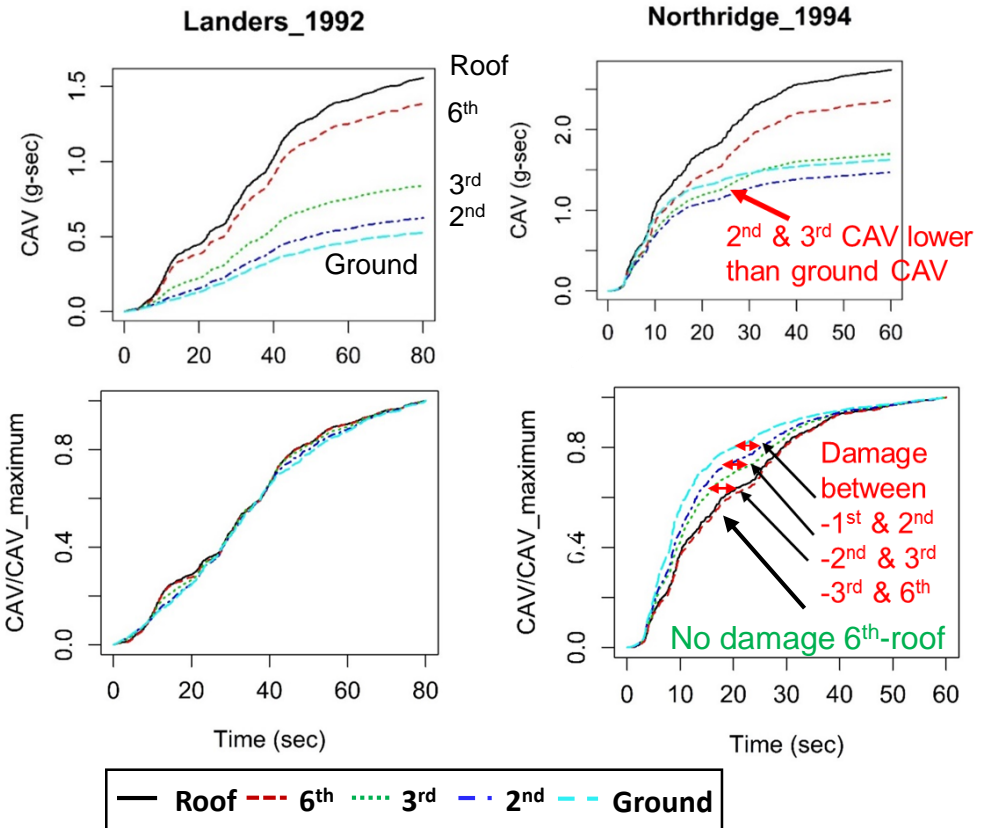
# CAV & Damage



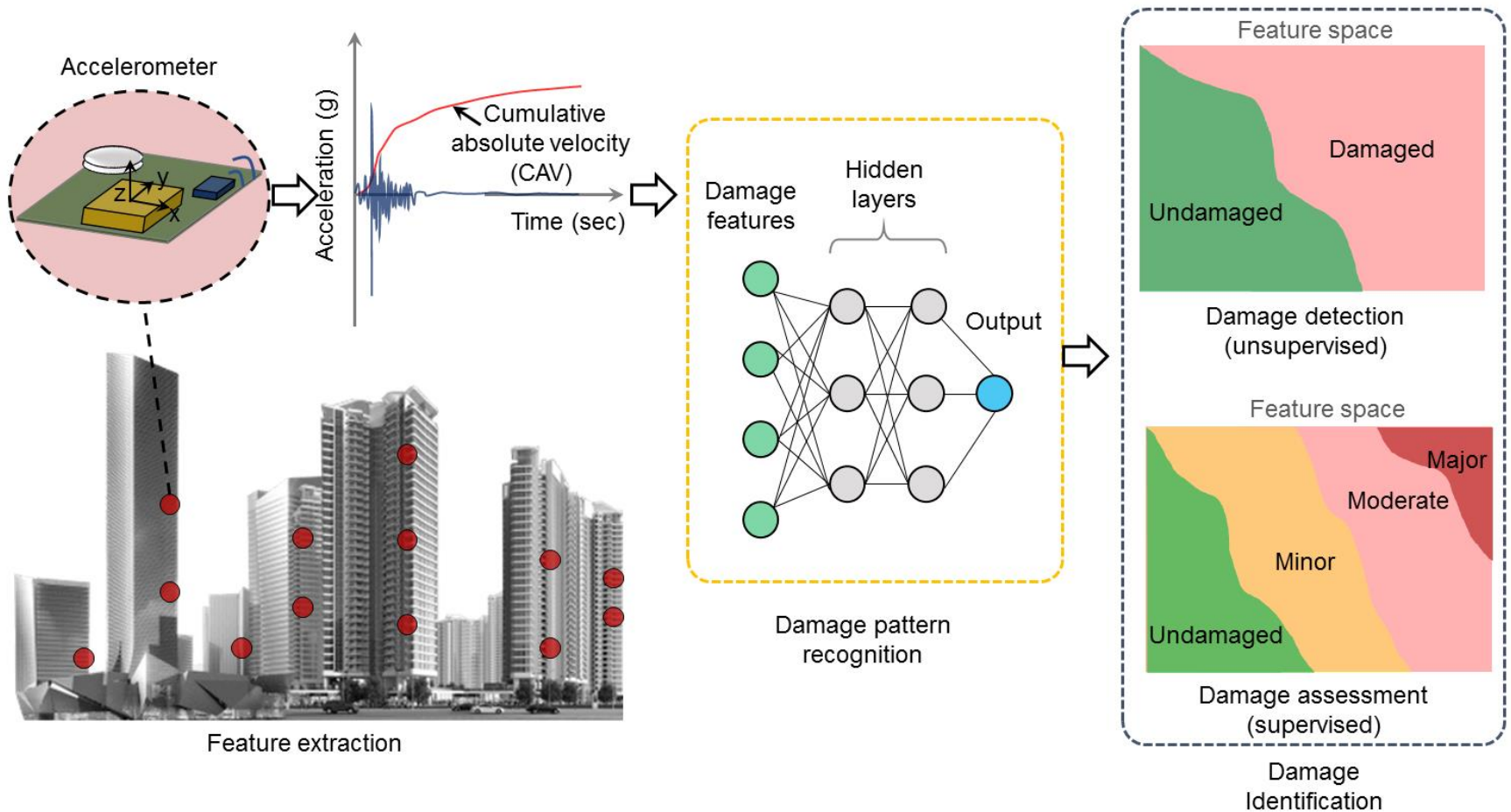
Van Nuys - 7-story Hotel  
(CSMIP Station No. 24386)



- Actual damage at ground, 2<sup>nd</sup>, 3<sup>rd</sup> & 4<sup>th</sup> floors
- Undamaged / baseline case from 1992 Landers earthquake



# CAV in Machine Learning

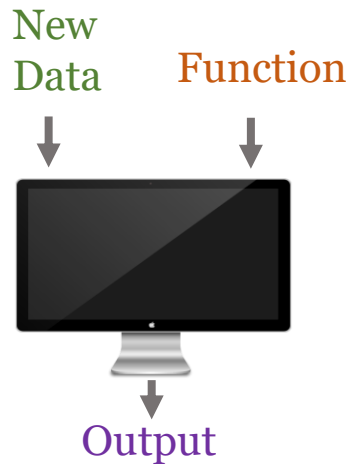


# Machine Learning (ML)

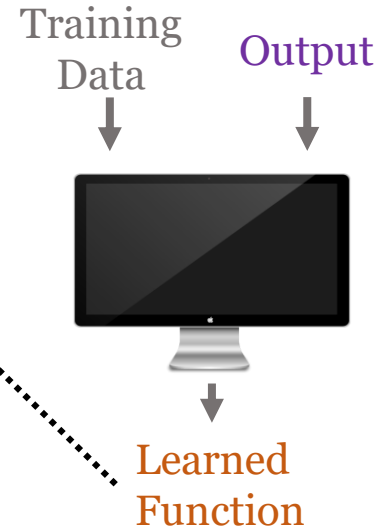
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“ML is the science of making computers learn & act as humans to improve their learning over time in autonomous fashion, using data & information (observations & real-world interactions).”

## Traditional Programming



## Machine Learning





# Supervised & Unsupervised Learning

- Supervised learning is inferring a function from **labeled training data**.
- Unsupervised learning is inferring function from **unlabeled training data**.

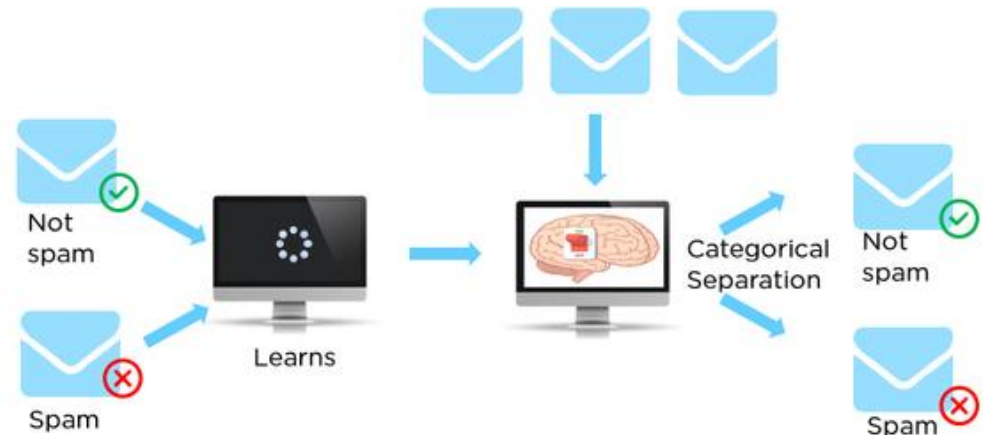
- **Supervised learning**

- Regression – continuous output
- **Classification** – discrete output

- **Unsupervised learning**

- Clustering – unknown output

## Classification Example



Features: words, characters, size, etc.

# Supervised & Unsupervised Learning

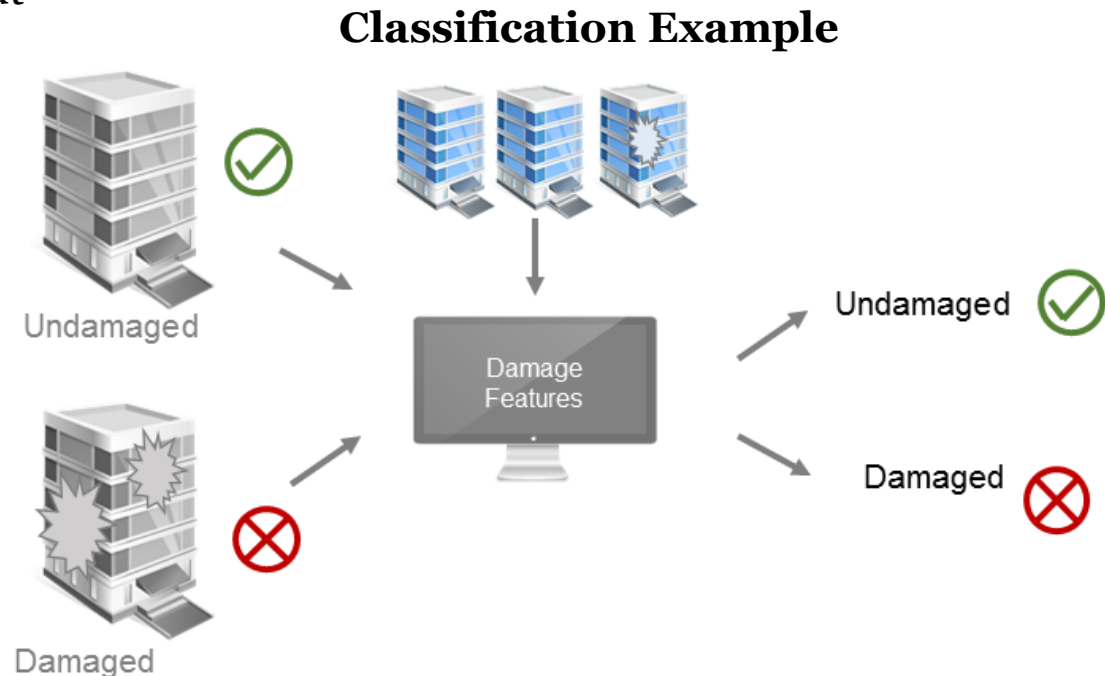
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- **Supervised learning**

- Regression – continuous output
- **Classification** – discrete output

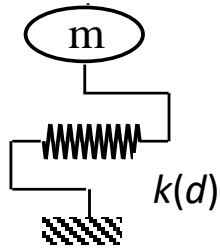
- **Unsupervised learning**

- Clustering – unknown output



# SDOF Analysis

## SDOF model



Feature Symbol	Theoretical Definition	Mathematical Definition
$CAV_s$	CAV value at a sensor	$CAV_s = CAV = \int_0^T  \ddot{u}(t)  dt$
$R_{CAV}$	Ratio of floor CAV response to Linear CAV response	$R_{CAV} = \frac{CAV_s}{CAV_l}$
$S_{CAV}$	Change in effective duration compared to a linear model	$S_{CAV} = (D_{5-75,s} - D_{5-75,l}) \times 100\%$
$\Delta_{NCAV}$	Total absolute deviation of NCAV (Normalized CAV with $CAV_{max}$ ) compared to a linear model	$\Delta_{CAV} = \text{abs}[(A_s - A_l)/A_l] \times 100\%$

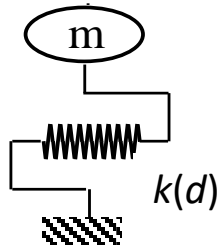
## SDOF Results: TEST-1

Input Features	OLR	LR	ANN_10	ANN_100	SVM
CAV	80.54	82.88	80.54	81.71	79.38
$R_{CAV}$	87.16	86.72	88.72	89.49	88.33
$\Delta_{CAV}$	75.10	75.10	75.10	77.04	75.10
<b>CAV, <math>R_{CAV}</math></b>	<b>90.27</b>	89.44	88.72	90.66	<b>91.05</b>
$R_{CAV}, \Delta_{CAV}$	86.77	84.72	89.11	87.94	87.94
CAV, $\Delta_{CAV}$	80.54	83.27	80.54	81.32	79.38
CAV, $R_{CAV}, \Delta_{CAV}$	90.27	89.05	90.27	90.66	89.88

CAV &  $R_{CAV}$  used together as features give highest accuracy for both test cases

# SDOF Analysis

## SDOF model



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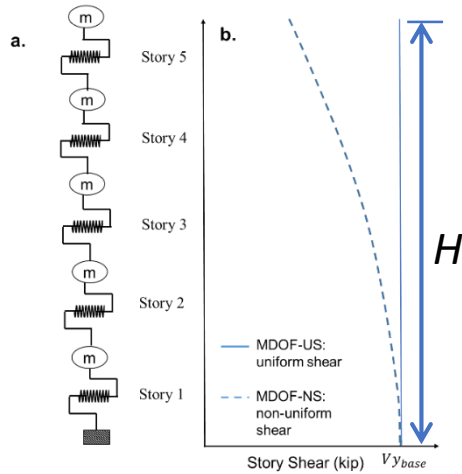
## SDOF Results: TEST-2

Input Features	OLR	LR	ANN_10	ANN_100	SVM
CAV	36.67	12.50	18.33	15.83	8.33
$R_{CAV}$	60.00	42.50	30.83	37.50	20.83
$\Delta_{CAV}$	61.67	45.00	42.50	40.00	21.67
<b>CAV, <math>R_{CAV}</math></b>	<b>74.14</b>	61.67	18.33	40.00	<b>25.00</b>
$R_{CAV}, \Delta_{CAV}$	65.83	45.00	60.00	40.00	22.50
CAV, $\Delta_{CAV}$	70.00	60.00	51.67	36.67	24.17
CAV, $R_{CAV}, \Delta_{CAV}$	70.00	61.67	38.33	54.17	25.00

CAV &  $R_{CAV}$  used together as features give highest accuracy for both test cases

# MDOF Analysis

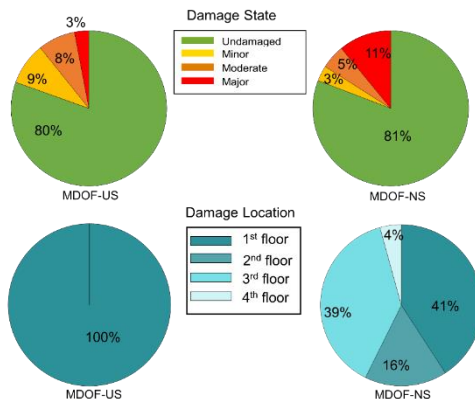
A MDOF model representing a 5-story structure



➤ Class specific **recall** values for the two models

Class	MDOF-US	MDOF-NS
Undamaged	0.993	0.993
Minor	0.286	0.000
Moderate	0.781	0.463
Major	0.922	0.966

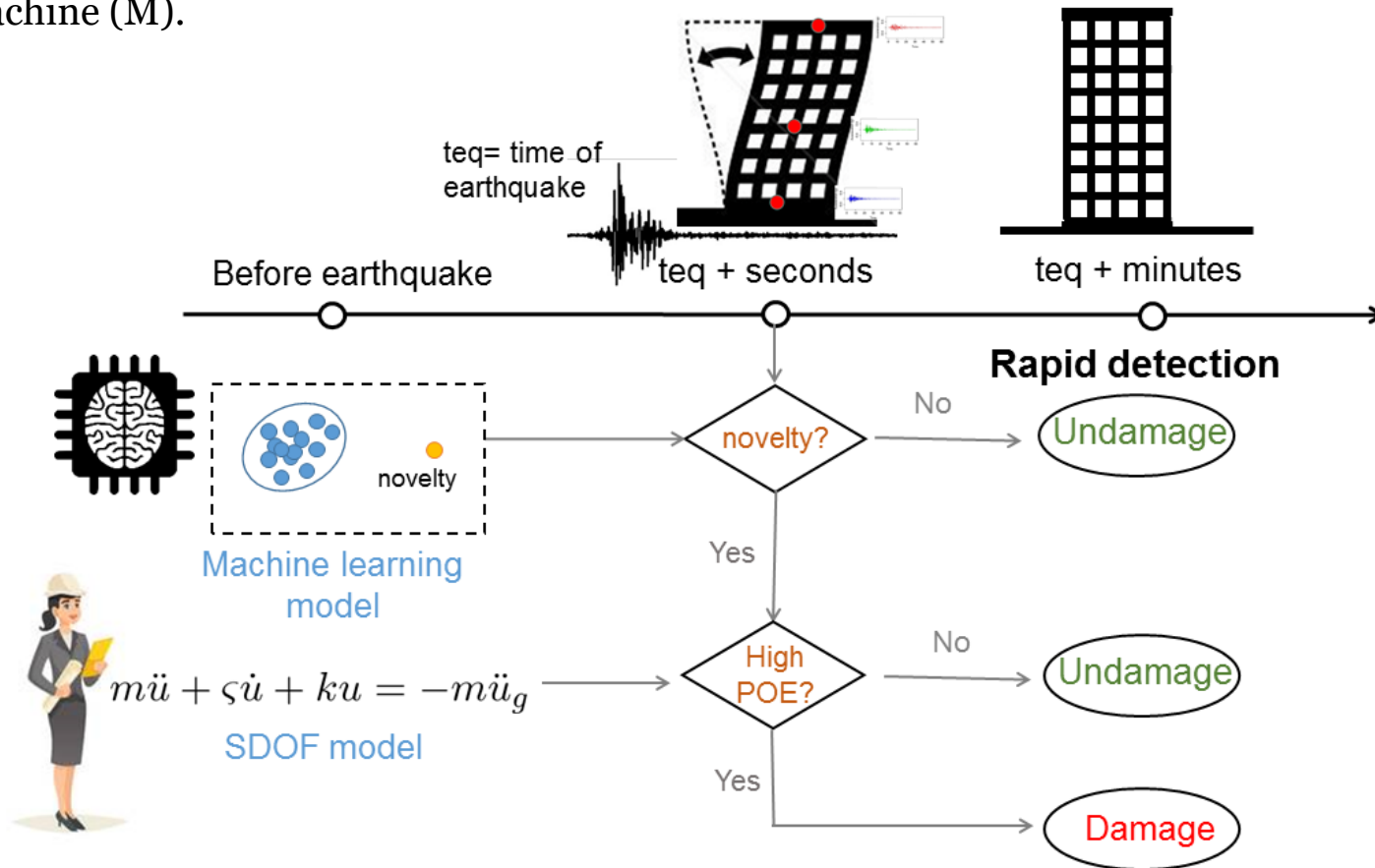
➤ Locations were identified correctly even when damage locations were uncertain with  $CAV$  and  $R_{CAV}$



MDOF model	Test set	Location accuracy
MDOF-US	TEST-1	97.5%
	TEST-2	97.5%
MDOF-NS	TEST-1	93.0%
	TEST-2	95.0%

# Human-Machine Collaboration (H-MC)

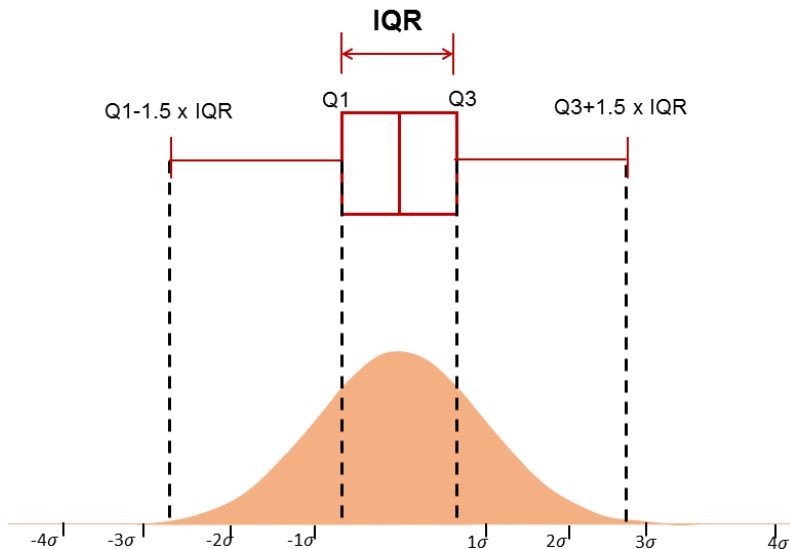
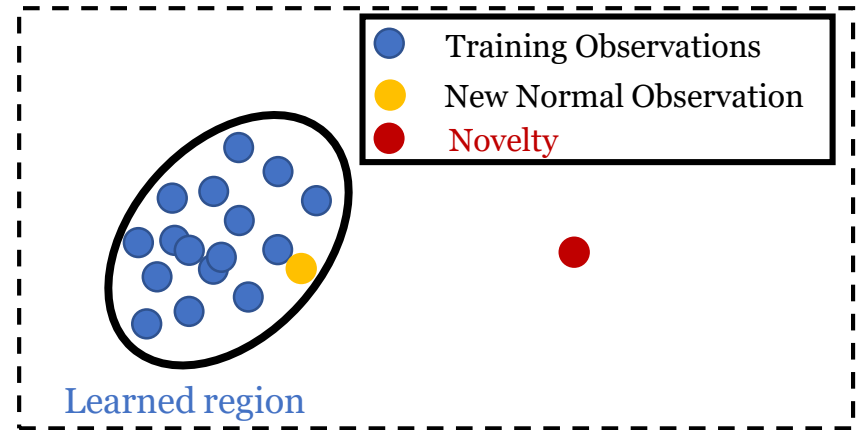
Human-Machine collaboration (H-MC) is a framework in which **humans co-work with machines** to complete specific tasks by **using the particular strengths** of both human (H) and machine (M).



# Novelty Detection

Between supervised and unsupervised learning, lies one class classification.

✓ Available data from only one class.

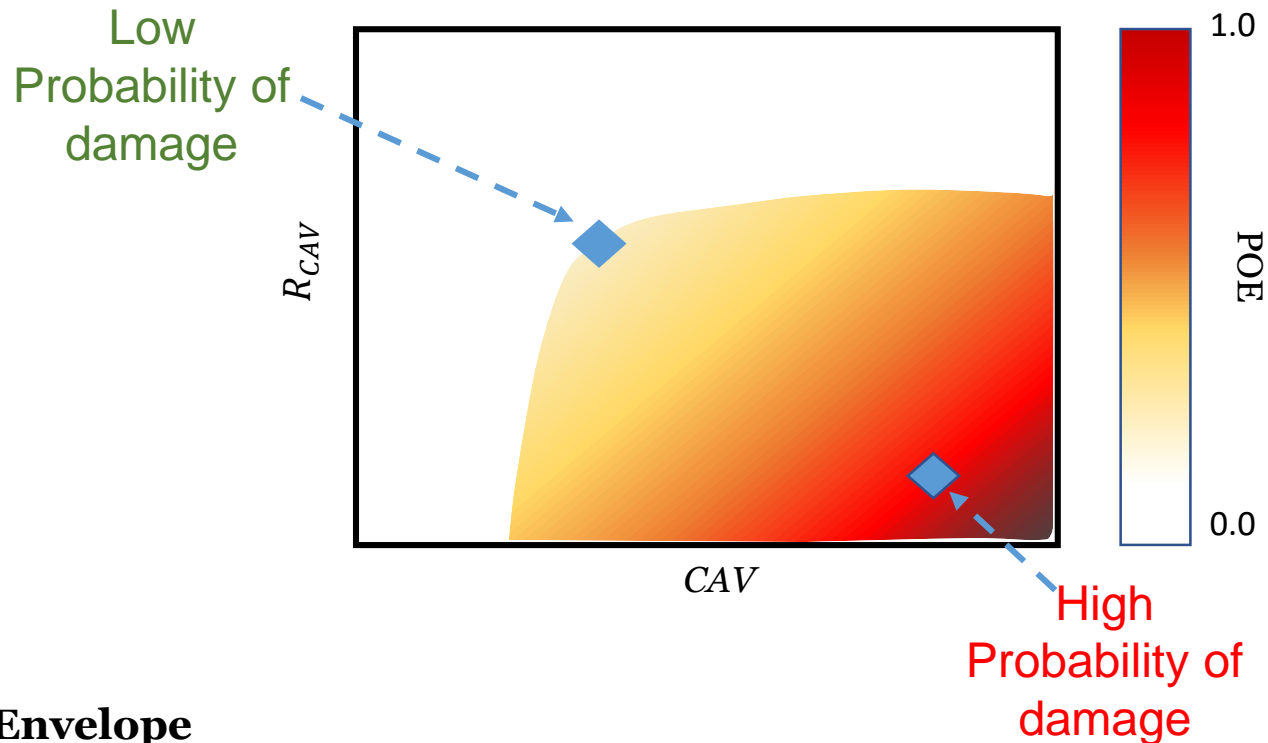


## Novelty model:

- Non-parametric (uncertain) distribution from training data
- Distance measure to detect novelty  $\geq 1.5 \times IQR$

**Limitation:** Novelty detection alone may result in False Positive (FP) due to lack of data from rare (strong but undamaging) shaking.

# POE Envelope

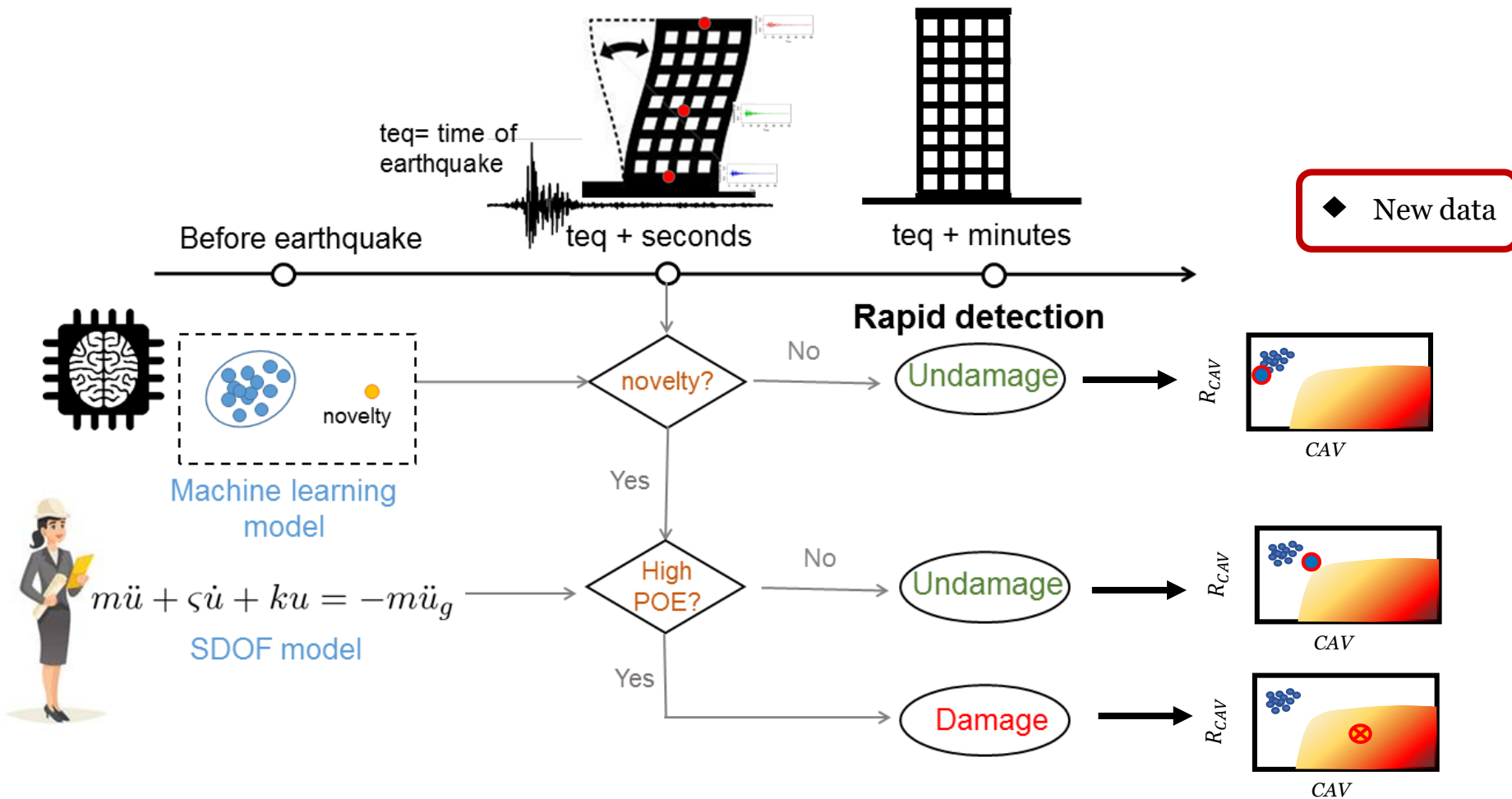


## POE Envelope

- Structure-specific SDOF model with basic data
- NTHA using 1,710 ground motions
- Joint distribution using  $CAV$  &  $R_{CAV}$  of damaging events



# H-MC for Damage Detection



# CSMIP Buildings

CGS CSMIP-89494  
Eureka - 5-story Residential Bldg.



CGS CSMIP-12267  
Hemet - 4-story Hospital



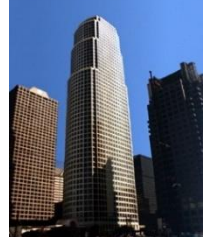
CGS CSMIP-01260  
El Centro - Imperial Co. Services Bldg



CGS CSMIP-03603  
San Diego - 19-story Commercial Bldg



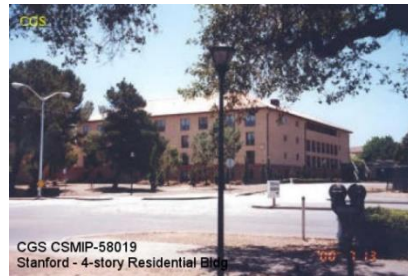
CGS CSMIP-04423  
Los Angeles - 54-story Office Bldg



CGS CSMIP-23634  
San Bernardino - 5-story Hospital

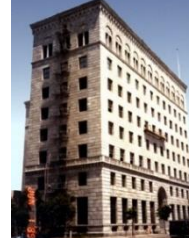


CGS CSMIP-24322  
Sterling Oaks - 13-story Commercial Bldg

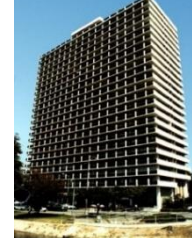


CGS CSMIP-58019  
Stanford - 4-story Residential Bldg

CGS CSMIP-26478  
Los Angeles - 9-story Office Bldg



CGS CSMIP-08483  
Dubai - 24-story Residential Bldg



CGS CSMIP-58154  
Hayward - 13-story CSLH Admin. Bldg



CGS CSMIP-24386  
Van Nuys - 7-story Hotel



CGS CSMIP-24463  
Los Angeles - 5-story Warehouse



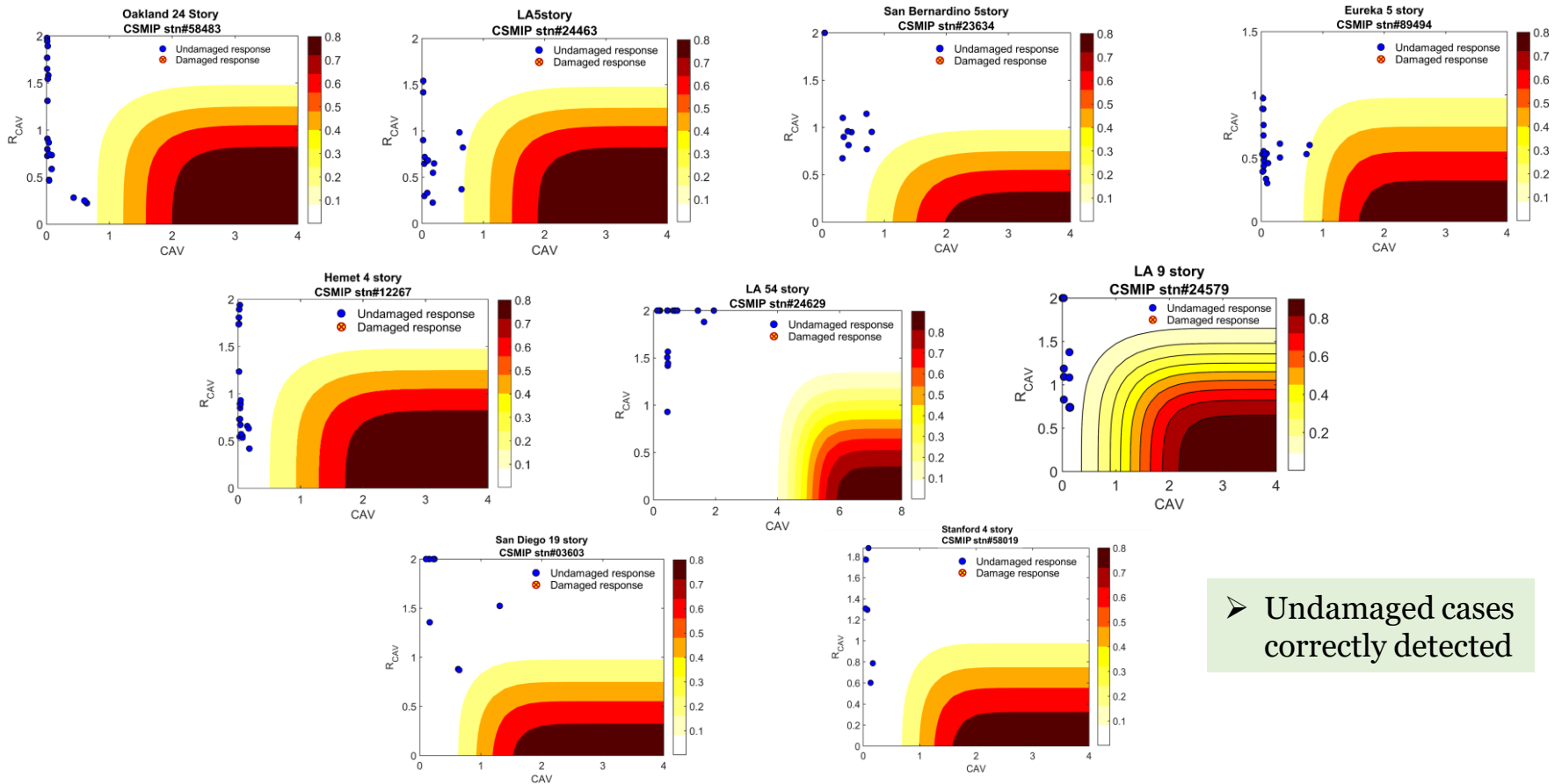
CGS CSMIP-57357  
San Jose - 13-story Govt Office Bldg



CGS CSMIP-58196  
Berkeley - 5-story Parking Structure

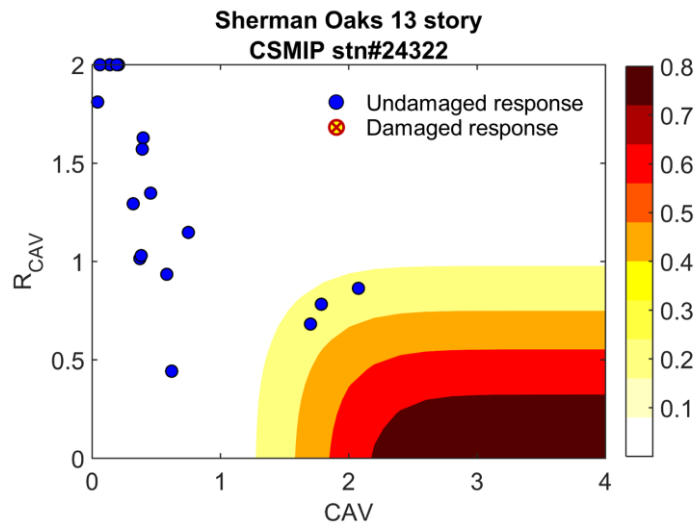


# Undamaged Buildings

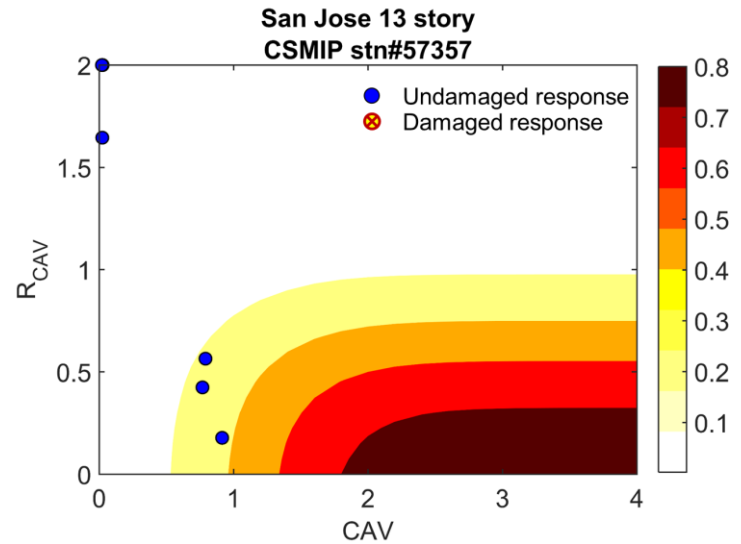


➤ Undamaged cases correctly detected

# Undamaged Buildings

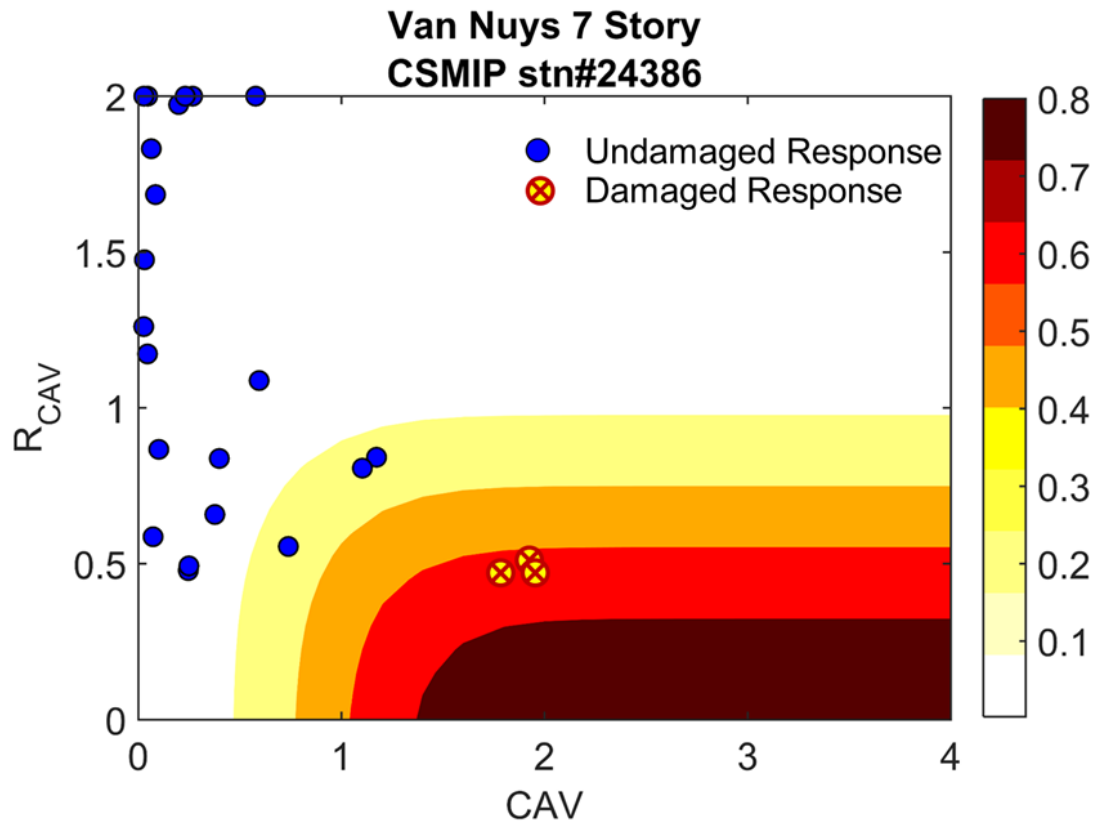


➤ Undamaged cases correctly detected



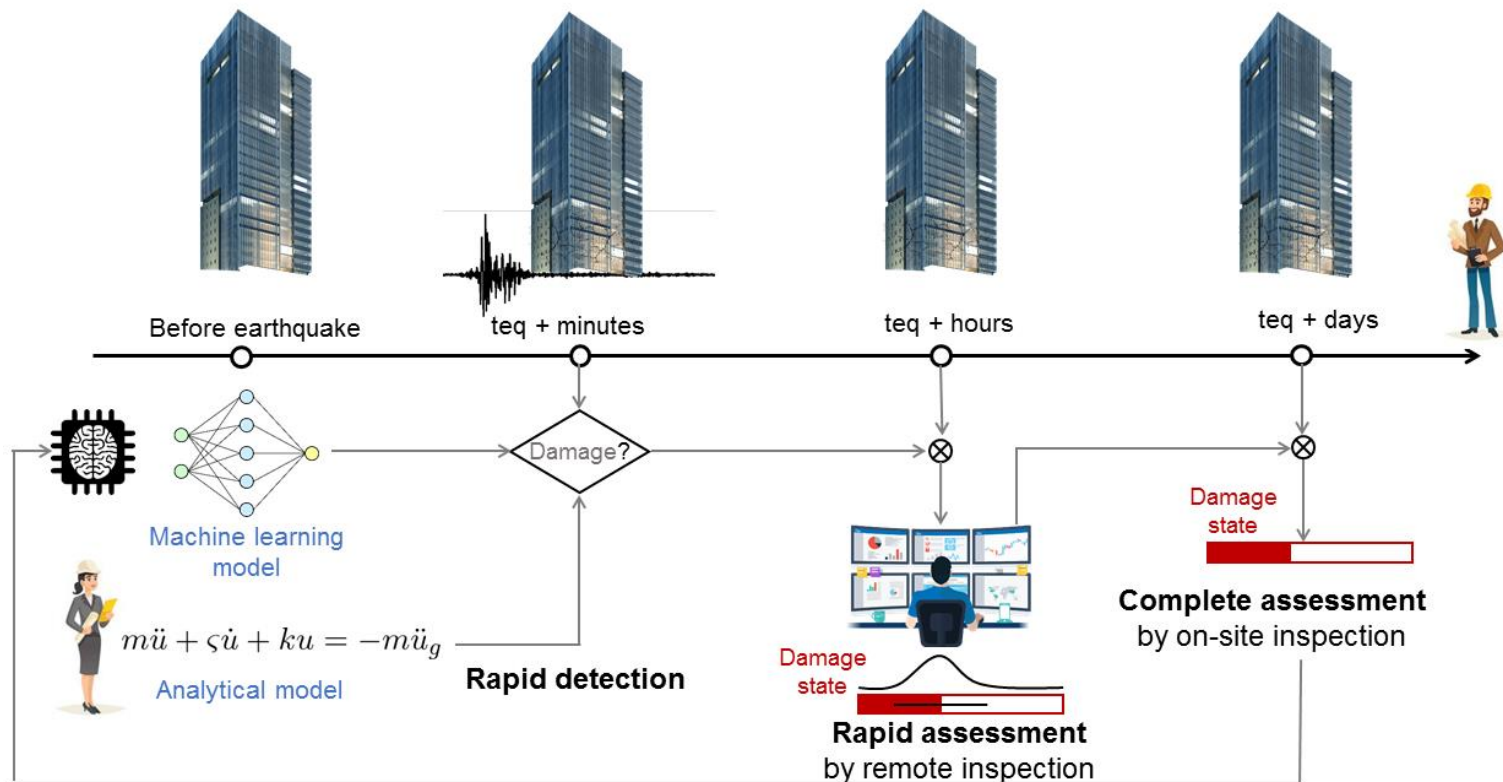
➤ Novelty only gives *FP*

# Damaged Buildings



➤ Damaged case correctly detected

# The Future



### **Acknowledgements:**

Dr. Selim Günay, Dr. Umberto Alibrandi, & Dr. Yousef Bozorgnia.

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# Thank You!