2nd JCI & ACI Joint Seminar
-Resilience of Concrete Structures-
(2015.7.13)

Recent Shaking Table Tests of RC Building Model Structures

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Topics

1. 20 Storied Moment –Frame Building Subjected to Long Period and Long Duration Ground Motion

   Cooperation Study of Obayashi, Kajima, Kobori, Shimizu, Taisei, Takenaka, and BRI: (2010-2012)
   Project of servicing the architectural standard, Thema 27-1, Sponsored by MLIT （国交省）

2. 6 Storied Wall-Frame Building Subjected to Observed Ground Motion at Kobe in 1995

   Cooperation Study of Obayashi, Kajima, Kobori, Shimizu, Taisei, Takenaka, Kyoto University, and NIED: (2010-2012)
   Project Title: Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters, Sub-Pro 2: Maintenance and Recovery of Functionality in Urban Infrastructures, Quantification of Collapse Margins in Reinforced Concrete Buildings,
   Sponsored by MEXT（文科省）

View of Specimens

Topic 1: High Rise RC
MLIT's Project 国交省
Tested in 2012, Aug.

Topic 2: Low Rise RC
MEXT's Project 文科省
Tested in 2015, Jan.

Common Testing Facility
E-DEFENSE of NIED

Aim of Shaking Table Test

- Reproducing of Past Phenomena
  - Response and Damage of Past Buildings for Kobe Earthquake
- Verification
  - Design Codes or Concepts
  - Structural Detailing, etc.

Topics 1 and 2

- Finding of New (Future) Phenomena
  - Response and Damage of Current Buildings for Long Period Ground Motions

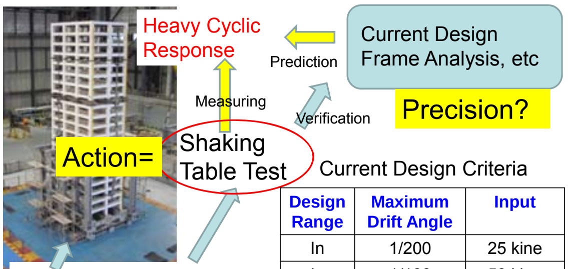
Topics 2 and 1

Contents of Topic 1: High Rise RC

1. Objective 目的
2. Specimen 試験体
3. Input Motions 入力波形
4. Test Results 実験結果
5. Analysis 解析
6. Conclusions まとめ

Object

To Grasp Precision of the Current Analytical Methods for Predicting Behavior of High Rise Reinforced Concrete Building Subjected to Long Period and Long Duration Ground Motions



Long Period and Long Duration Ground Motions

Current Design Criteria

Design Range	Maximum Drift Angle	Input
In	1/200	25 kine
In	1/100	50 kine
Over	1/50?	Very Large

Specimen

20 Storied, ¼-Scaled Model, 3 × 2 spans, Moment-Resisting Frame

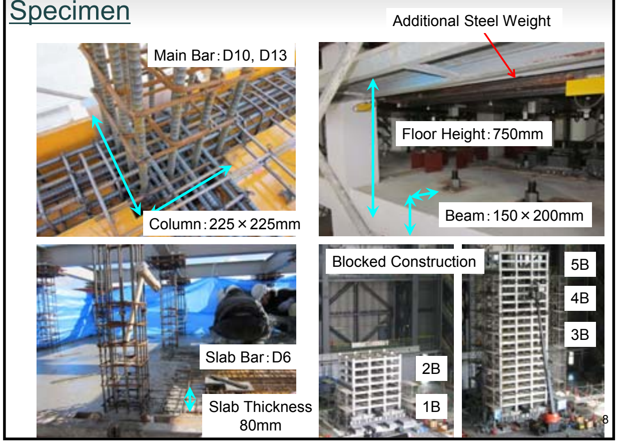
Total Height = 15m

Prototype Building:
Designed in late 1990's

High Strength Material:
Concrete: Fc=30 to 60N/mm2
Main Rebar: σy=495 N/mm2
Hoop Rebar: σy=695 N/mm2

Total Weight: 5000kN approximately
Including Foundation and Protectors
Total Floor Weight: 3600kN approximately
Including Additional Steel Weight

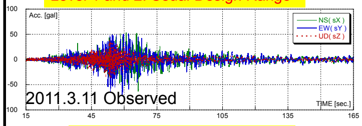
Specimen


Additional Steel Weight
Main Bar：D10, D13
Column：225 × 225mm
Floor Height：750mm
Beam：150 × 200mm
Slab Bar：D6
Slab Thickness 80mm
Blocked Construction
5B
4B
3B
2B
1B

Shaking Program and Summarized Results

Two Input Waves 3.11 Observed / Nankai Trough Calculated
Three Response Target Level 1 , Level 2, and Ultimate
→Magnify Wave Amplitude

Level 1 and 2: Usual Design Range

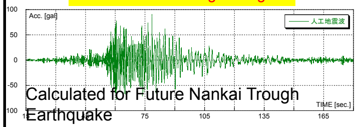


2011.3.11 Observed

CASE	MF	Max. Drift Angle
1-5	100%	1/234
2-2	200%	1/137
2-6	300%	1/86

MF: Magnification Factor

Ultimate: Over-Design Range

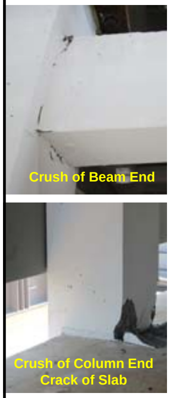


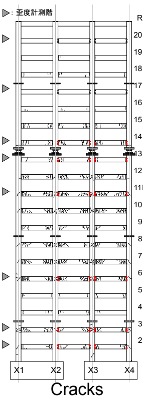
Calculated for Future Nankai Trough Earthquake

CASE	MF	Max. Drift Angle
3-2	150%	1/64
3-5	200%	1/35

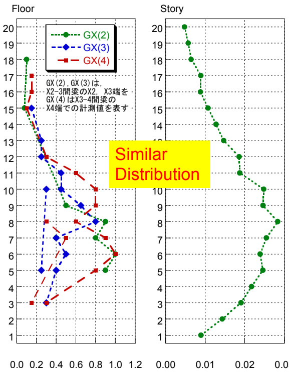
Compressed Time Axis (1/2) ….Similarity Law of Scaled Test

Test Results: Damage Inspection


Crush of Beam End
Crush of Column End
Crack of Slab

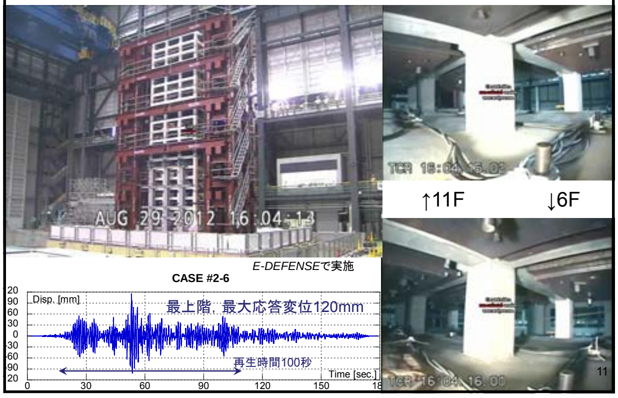

▷：歪度計測階
R
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
X1
X2
X3
X4

Cracks

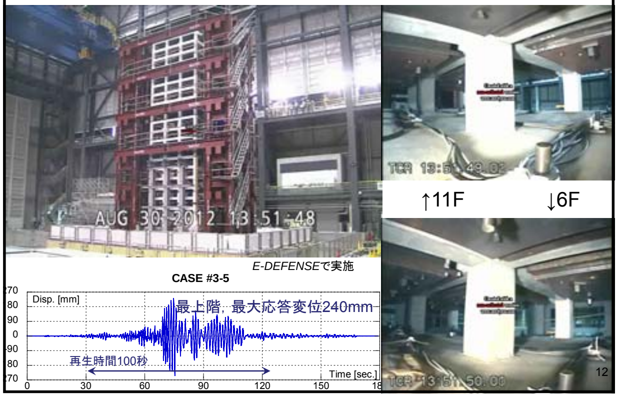


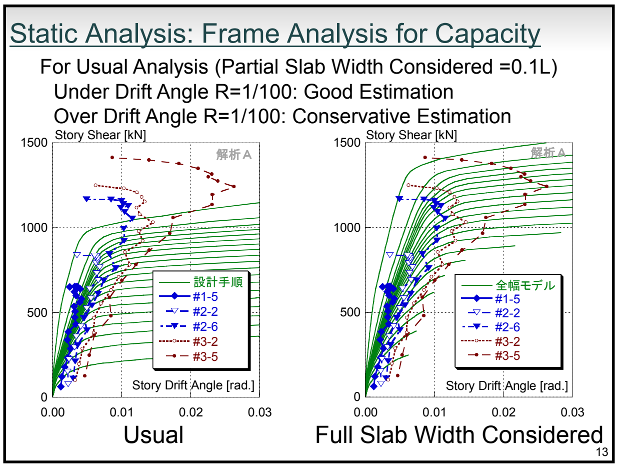
Crack Width Deformation

Test Results: Video (2nd Design Level)


AUG 29 2012 16:04:13
TCR 16:04:15.02
↑11F
↓6F
E-DEFENSEで実施
CASE #2-6
Disp. [mm]
最上階，最大応答変位120mm
再生時間100秒
Time [sec.]
20
90
60
30
0
30
60
90
20
0
30
60
90
120
150
18
TCR 16:04:16.00

Test Results: Video (Over-Design Level)


AUG 30 2012 13:51:48
TCR 13:51:49.02
↑11F
↓6F
E-DEFENSEで実施
CASE #3-5
Disp. [mm]
最上階，最大応答変位240mm
再生時間100秒
Time [sec.]
70
80
90
0
90
80
70
0
30
60
90
120
150
18
TCR 13:51:50:00

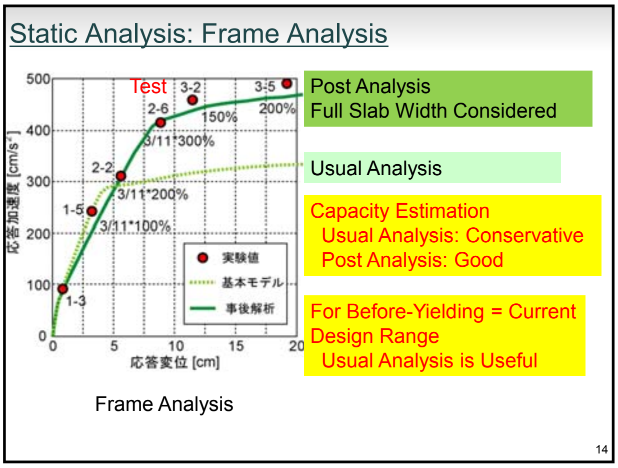


Static Analysis: Frame Analysis for Capacity

For Usual Analysis (Partial Slab Width Considered =0.1L)
Under Drift Angle R=1/100: Good Estimation
Over Drift Angle R=1/100: Conservative Estimation

Usual

Full Slab Width Considered



Static Analysis: Frame Analysis

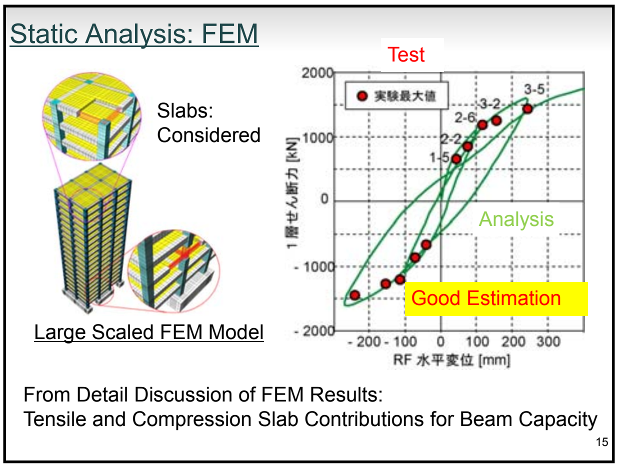
Post Analysis
Full Slab Width Considered

Usual Analysis

Capacity Estimation
Usual Analysis: Conservative
Post Analysis: Good

For Before-Yielding = Current Design Range
Usual Analysis is Useful

Frame Analysis

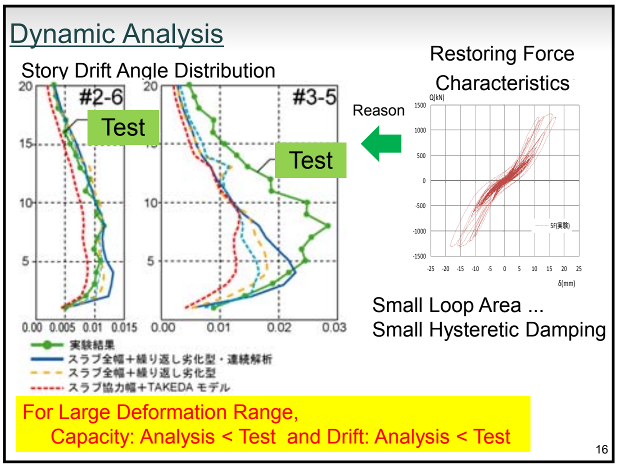


Static Analysis: FEM

Slabs: Considered

Large Scaled FEM Model

From Detail Discussion of FEM Results:
Tensile and Compression Slab Contributions for Beam Capacity



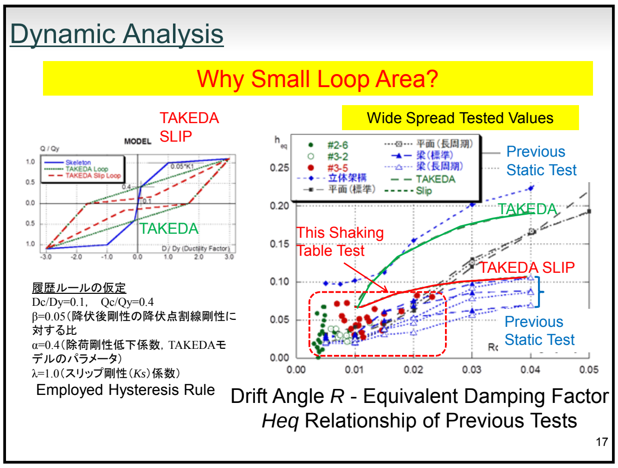
Dynamic Analysis

Story Drift Angle Distribution

Restoring Force Characteristics

Small Loop Area ...
Small Hysteretic Damping

For Large Deformation Range,
Capacity: Analysis < Test and Drift: Analysis < Test



Dynamic Analysis

Why Small Loop Area?

履歴ルールの仮定
Dc/Dy=0.1,　Qc/Qy=0.4
β=0.05（降伏後剛性の降伏点割線剛性に対する比
α=0.4（除荷剛性低下係数，TAKEDAモデルのパラメータ）
λ=1.0（スリップ剛性（*Ks*）係数）

Employed Hysteresis Rule

Wide Spread Tested Values

Drift Angle *R* - Equivalent Damping Factor *Heq* Relationship of Previous Tests

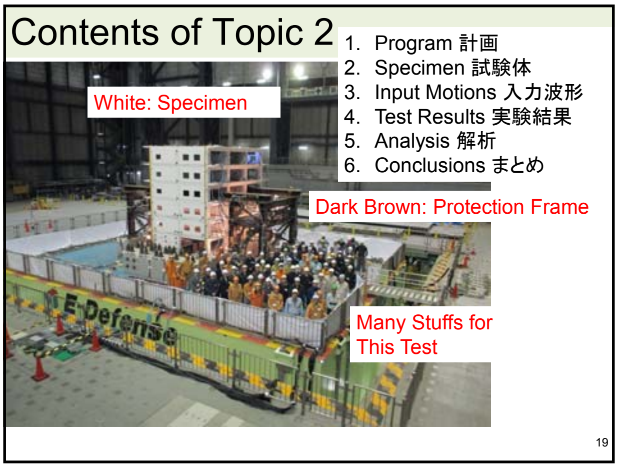
Conclusion

1. Test

- Shaking Table Test of ¼ Scaled and 20 Storied Reinforced Concrete Building
- Long Period and Long Duration Ground Motions
- Maximum Response Story Drift Angle R of 1/35

2. Analysis

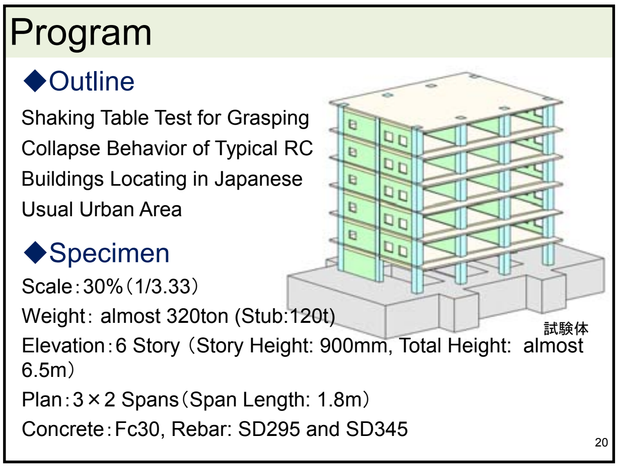
- Good Evaluation through Current Analysis Methods for Small to Medium Response
- Insufficient Evaluation for Large Response
- Slab Contribution and Hysteretic Damping are Discussed



Contents of Topic 2

1. Program 計画
2. Specimen 試験体
3. Input Motions 入力波形
4. Test Results 実験結果
5. Analysis 解析
6. Conclusions まとめ

White: Specimen
Dark Brown: Protection Frame
Many Stuffs for This Test
E-Defense



Program

◆Outline

Shaking Table Test for Grasping Collapse Behavior of Typical RC Buildings Locating in Japanese Usual Urban Area

◆Specimen

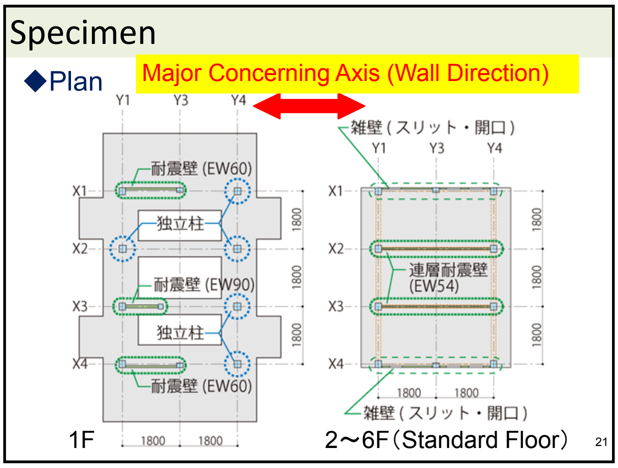
Scale：30%（1/3.33）

Weight：almost 320ton (Stub:120t)

Elevation：6 Story（Story Height: 900mm, Total Height: almost 6.5m）

Plan：3×2 Spans（Span Length: 1.8m）

Concrete：Fc30, Rebar: SD295 and SD345



Specimen

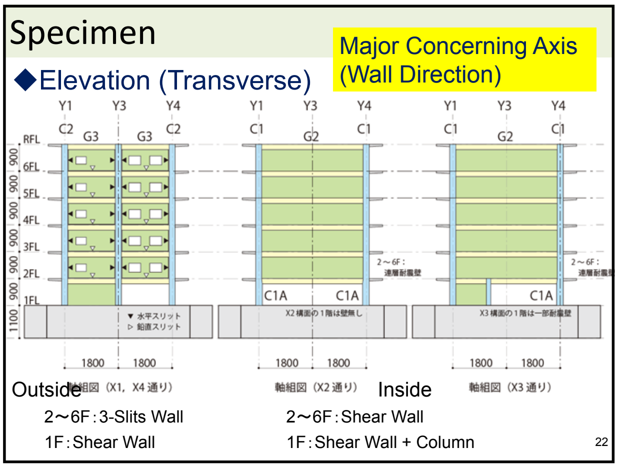
◆Plan

Major Concerning Axis (Wall Direction)

Y1
Y3
Y4
X1
X2
X3
X4
耐震壁 (EW60)
独立柱
耐震壁 (EW90)
独立柱
耐震壁 (EW60)
1800
1800
1800
雑壁（スリット・開口）
連層耐震壁 (EW54)
雑壁（スリット・開口）
1800
1800

1F

2～6F（Standard Floor）



Specimen

◆Elevation (Transverse)

Major Concerning Axis (Wall Direction)

Y1
Y3
Y4
C2
G3
G3
C2
C1
G2
C1
RFL
6FL
5FL
4FL
3FL
2FL
1FL
900
1100
C1A
C1A
C1A
2～6F：連層耐震壁
▼ 水平スリット
▷ 鉛直スリット
X2 構面の 1 階は壁無し
X3 構面の 1 階は一部耐震壁
1800
1800
軸組図（X1，X4 通り）
軸組図（X2 通り）
軸組図（X3 通り）

Outside

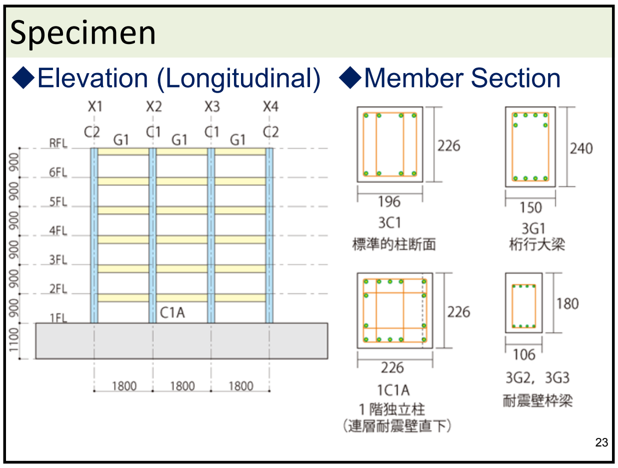
2～6F：3-Slits Wall

1F：Shear Wall

Inside

2～6F：Shear Wall

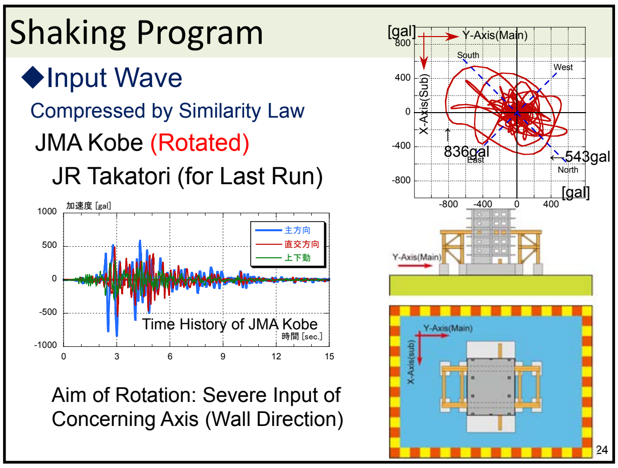
1F：Shear Wall + Column



Specimen

◆Elevation (Longitudinal)　◆Member Section

X1
X2
X3
X4
C2
G1
C1
G1
C1
G1
C2
RFL
6FL
5FL
4FL
3FL
2FL
1FL
900
1100
C1A
1800
1800
1800
226
196
3C1
標準的柱断面
240
150
3G1
桁行大梁
226
226
1C1A
1 階独立柱
（連層耐震壁直下）
180
106
3G2，3G3
耐震壁枠梁



Shaking Program

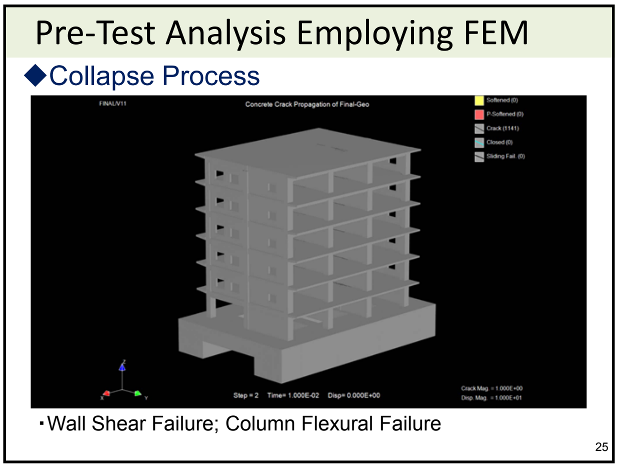
◆Input Wave

Compressed by Similarity Law

JMA Kobe (Rotated)

JR Takatori (for Last Run)

Aim of Rotation: Severe Input of Concerning Axis (Wall Direction)

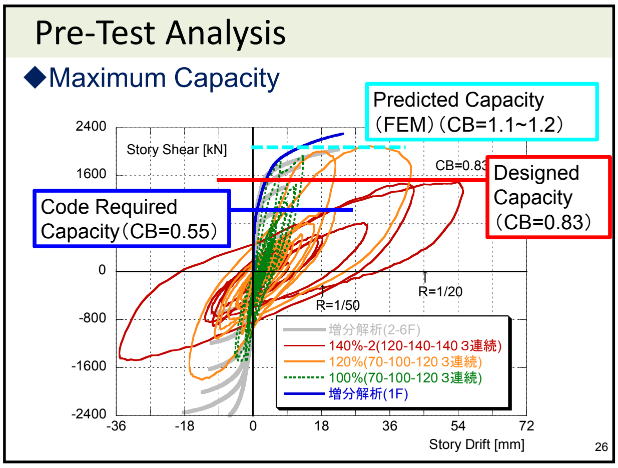


Pre-Test Analysis Employing FEM

◆Collapse Process

FINAL/V11
Concrete Crack Propagation of Final-Geo
Softened (0)
P-Softened (0)
Crack (1141)
Closed (0)
Sliding Fail. (0)
Z
X
Y
Step = 2 Time= 1.000E-02 Disp= 0.000E+00
Crack Mag. = 1.000E+00
Disp. Mag. = 1.000E+01

- Wall Shear Failure; Column Flexural Failure



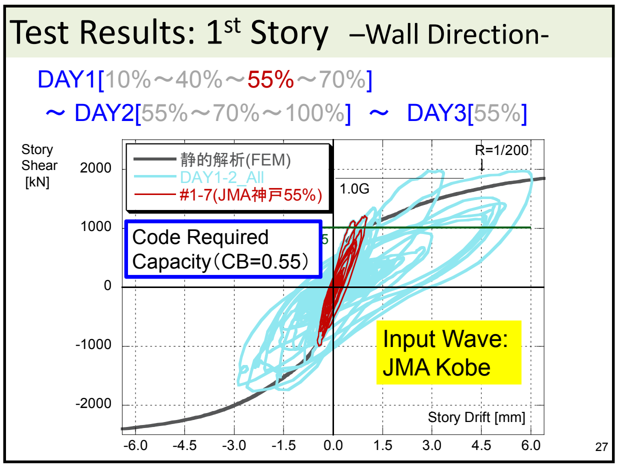
Pre-Test Analysis

◆Maximum Capacity

Predicted Capacity (FEM)（CB=1.1~1.2）

Code Required Capacity（CB=0.55）

Designed Capacity （CB=0.83）



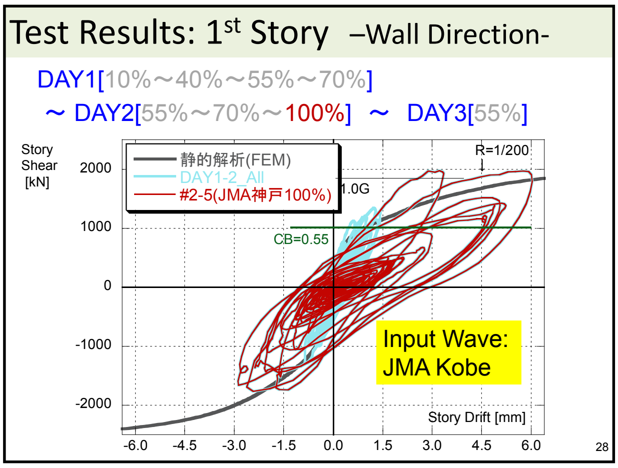
Test Results: 1st Story –Wall Direction-

DAY1[10%～40%～55%～70%]

～ DAY2[55%～70%～100%] ～ DAY3[55%]

Code Required Capacity（CB=0.55）

Input Wave: JMA Kobe

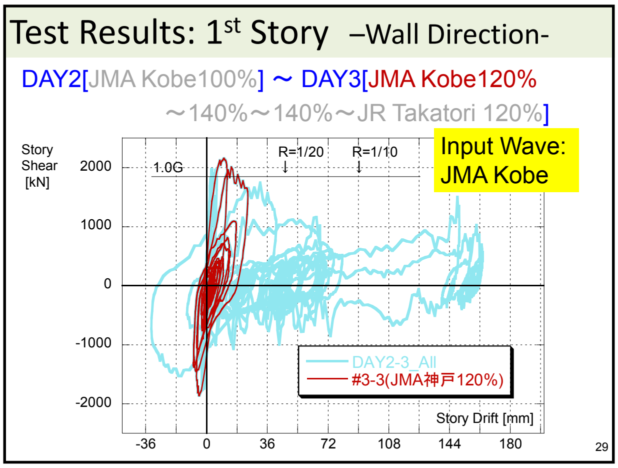


Test Results: 1st Story –Wall Direction-

DAY1[10%～40%～55%～70%]

～ DAY2[55%～70%～100%] ～ DAY3[55%]

Input Wave: JMA Kobe

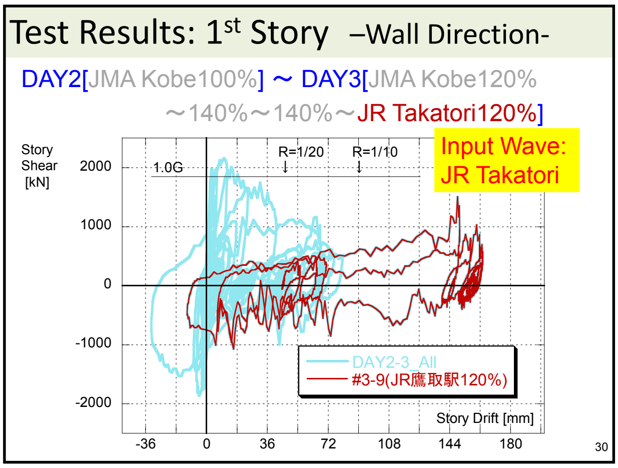


Test Results: 1st Story –Wall Direction-

DAY2[JMA Kobe100%] ～ DAY3[JMA Kobe120%

～140%～140%～JR Takatori 120%]

Input Wave: JMA Kobe



Test Results: 1st Story –Wall Direction-

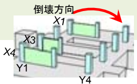
DAY2[JMA Kobe100%] ～ DAY3[JMA Kobe120%

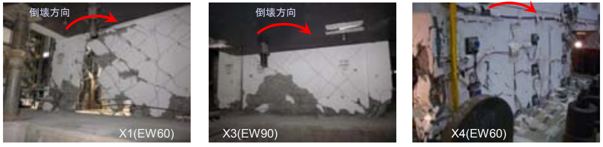
～140%～140%～JR Takatori120%]

Input Wave: JR Takatori

Damage

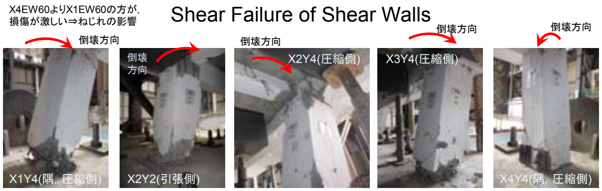
◆1st Story


倒壊方向
X1
X3
X4
Y1
Y4


倒壊方向
X1(EW60)
倒壊方向
X3(EW90)
X4(EW60)

X4EW60よりX1EW60の方が，
損傷が激しい⇒ねじれの影響

Shear Failure of Shear Walls

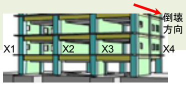

倒壊方向
X1Y4(隅，圧縮側)
倒壊
方向
X2Y2(引張側)
倒壊方向
X2Y4(圧縮側)
倒壊方向
X3Y4(圧縮側)
倒壊方向
X4Y4(隅，圧縮側)

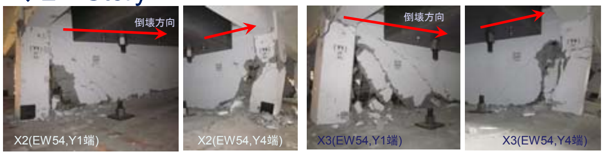
X1Y4がX4Y4より傾斜が
大きい⇒ねじれの影響

Flexural Failure of Columns (Bottom and Top)

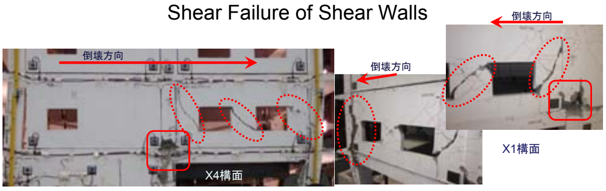
Damage

◆2nd Story


倒壊
方向
X1
X2
X3
X4


倒壊方向
X2(EW54,Y1端)
X2(EW54,Y4端)
倒壊方向
X3(EW54,Y1端)
X3(EW54,Y4端)

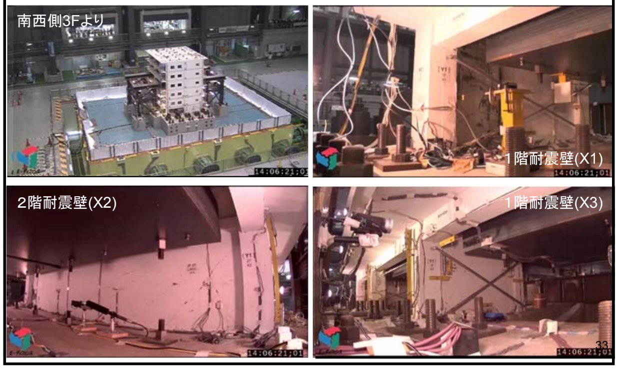
Shear Failure of Shear Walls


倒壊方向
倒壊方向
X4構面
倒壊方向
X1構面

Slit Wall Damage by Contact beyond Gap of Slit

Video

◆#3-5(JMA Kobe 140%-1)　1／2


南西側3Fより
1階耐震壁(X1)
2階耐震壁(X2)
1階耐震壁(X3)

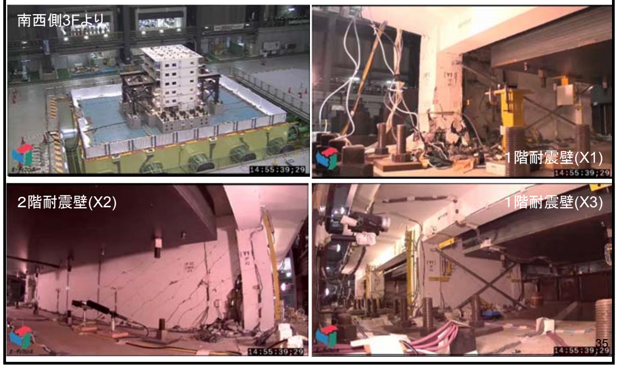
Video

◆#3-5(JMA Kobe 140%-1)　2／2

南東側より
1階独立柱(X2)
2階妻壁(X1)
1階独立柱(X1)

Video

◆#3-9(JR Takatori 120%)　1／2


南西側3Fより
1階耐震壁(X1)
2階耐震壁(X2)
1階耐震壁(X3)

Video

◆#3-9(JR Takatori 120%)　2／2

南東側より
1階独立柱(X2)
2階妻壁(X1)
1階独立柱(X1)

Conclusion

For code-required level of input motion,
damage of the structure is slight, and
continuous use is available.
For repeated inputs before maximum capacity,
deterioration of structural performance is slight.
Test value of maximum capacity is
almost twice of code-required level.
Collapse process during earthquakes is well grasped,
acquiring a lot of physical and mechanical data.
Pre-test analysis by FEM can predict
over-all behavior of the specimen

Thank You for Your Attention