

Reliability of Spatial Structures

deterministic approach

can we make it better by design?



22(Wed) May for JSCC, Prague

Ken'ichi Kawaguchi

IIS, the University of Tokyo

Vice-President of IASS



Spatial Structures

- Large Enclosures: Public Space, Function of Shelter

Reliability:

Life-safety

Function Continuity



<https://jp.trip.com/travel-guide/attraction/toronto/cn-tower-80782/>

Spatial Structures



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- Strategy for prevent Catastrophic Failure under Excessive Load
- How to control Non-structural components failure

Spatial Structures



<https://jp.trip.com/travel-guide/attraction/toronto/cn-tower-80782/>

- Large Enclosures: Public Space, Function of Shelter

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- Strategy for prevent Catastrophic Failure under Excessive Load
- How to control Non-structural components failure

Design: Load control, Damage control, Fail-Safe System, Human-Tolerance

IASS Recommendations

- Recommendations for the Design of Hyperbolic or other Similarly Shaped Cooling Towers, 1977 (WG 3)
- Recommendations for Guyed Masts, 1981 (WG4)
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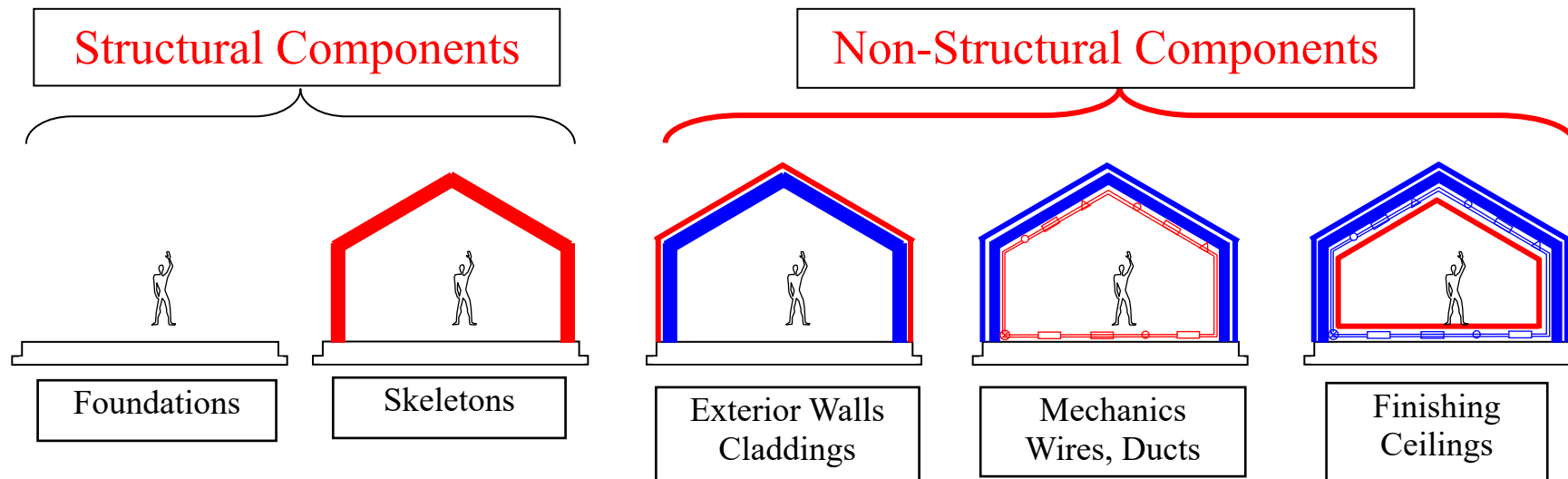
IASS Recommendations Soundness in Design

- Recommendations for the Design of Hyperbolic or other Similarly Shaped
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Components to be considered in design

Components

- Structural Components Foundations, Main Structures
- Non-Structural Components Exterior Walls, Claddings, Mechanical facilities.
- Users Life-Safety, Business Continuity
- Sound design, Load Control, Damage Control, Fail-Safe System, Human tolerance



Disturbance and load to be considered in design

Disturbance

- Time Dependent Damage -> Deterioration of Material -> Inspection
- Event Dependent Damage -> Severe Natural Disaster
(Strong wind, Heavy Snow, Earthquake)
Manmade Disaster
(War, Terror Attack, Vandalism, Fire...)

Load Control, Damage Control, Fail-Safe System, Human tolerance

Heavy Snow (including rain after snow)

Reliability:

Life-safety -> How to prevent Catastrophic Failure u. Excessive Load
(collapse without enough evacuation time)

Function Continuity, Business Continuity

-> How to prevent accidental and unexpected failure

Design: Load control, Damage control, Fail-Safe System, Human-Tolerance

Catastrophic collapse of Spatial Structures by Heavy Snow,

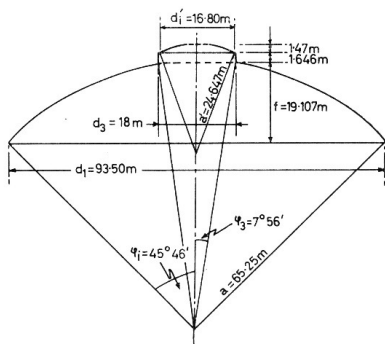
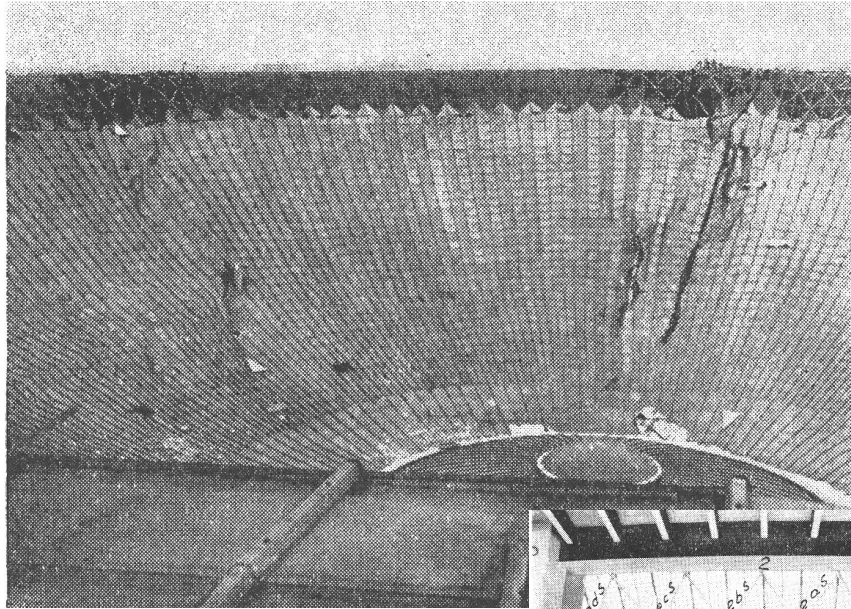
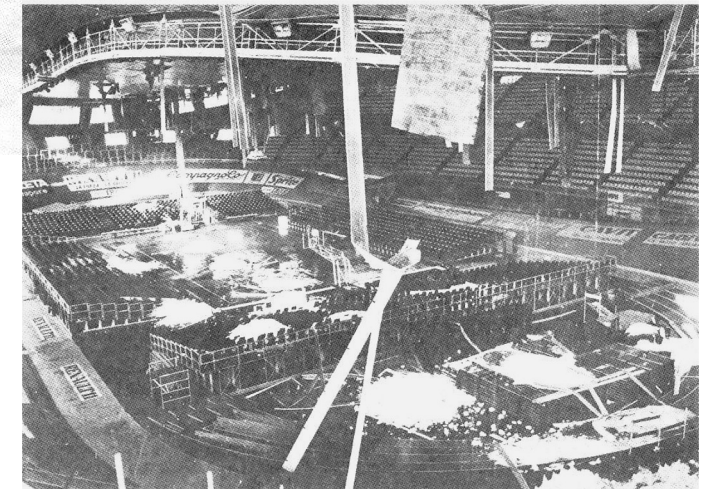
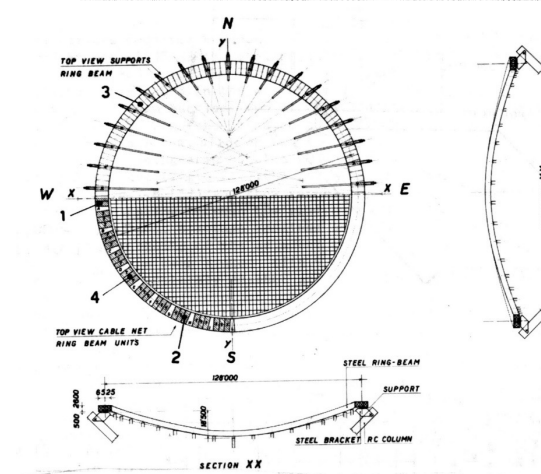
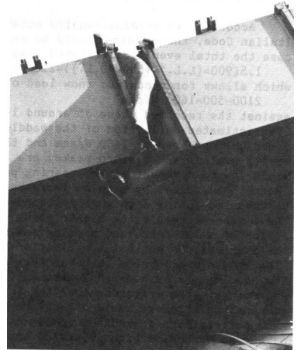
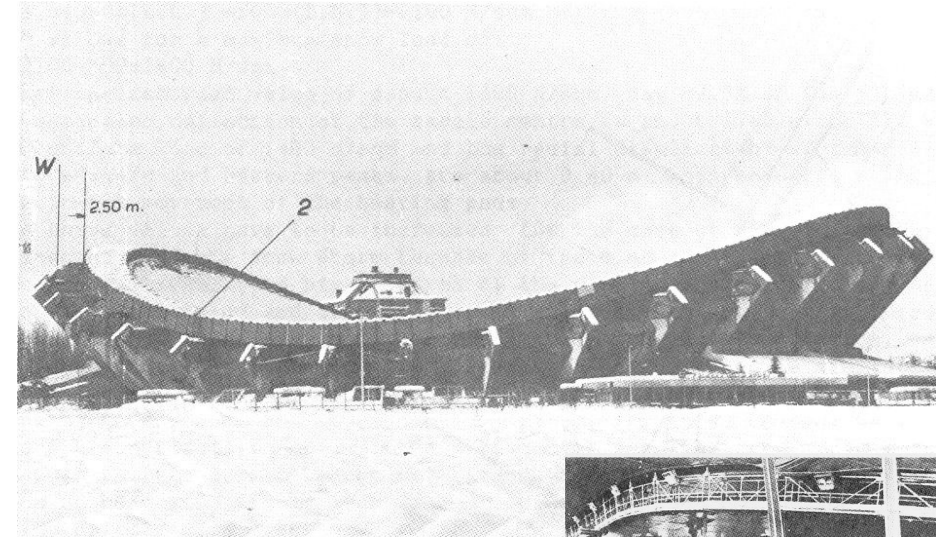
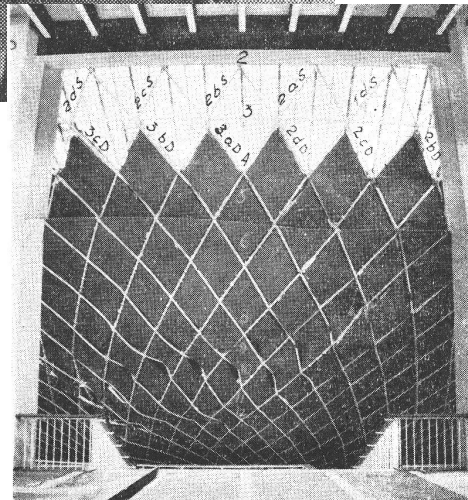


Figure 1. Geometric elements of the dome and the lantern.



Bucharest Dome (Romania) Jan.30,1963

Milan Sports Palace under Heavy Snow, 1985

Ken'ichi Kawaguchi, IASS

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Catastrophic collapse of Spatial Structures by Heavy Snow, 2004-2006



Swimming Pool in Moscow,
28 dead, 193 injured
Feb.14, 2004
Completed in 2002



Ice skate link, Bad Reichenhalla
in Germany, Jan.2nd, 2006
11 killed, 30 injured,
Completed in 1970



Exhibition Hall, Katowice
in Poland, Jan.28th,2006,
65 dead, 170 injured
Completed in 1974



Catastrophic collapse of Spatial Structures by Heavy Snow, special case in Czeck, 2017



[Czech Republic roof collapse results in no injuries \(VIDEO\) - Sports Illustrated](https://www.sportsillustrated.com/czech-republic-roof-collapse)

<https://ohsinsider.com/spot-the-safety-violation-9-tips-for-safely-clearing-snow-from-roofs>

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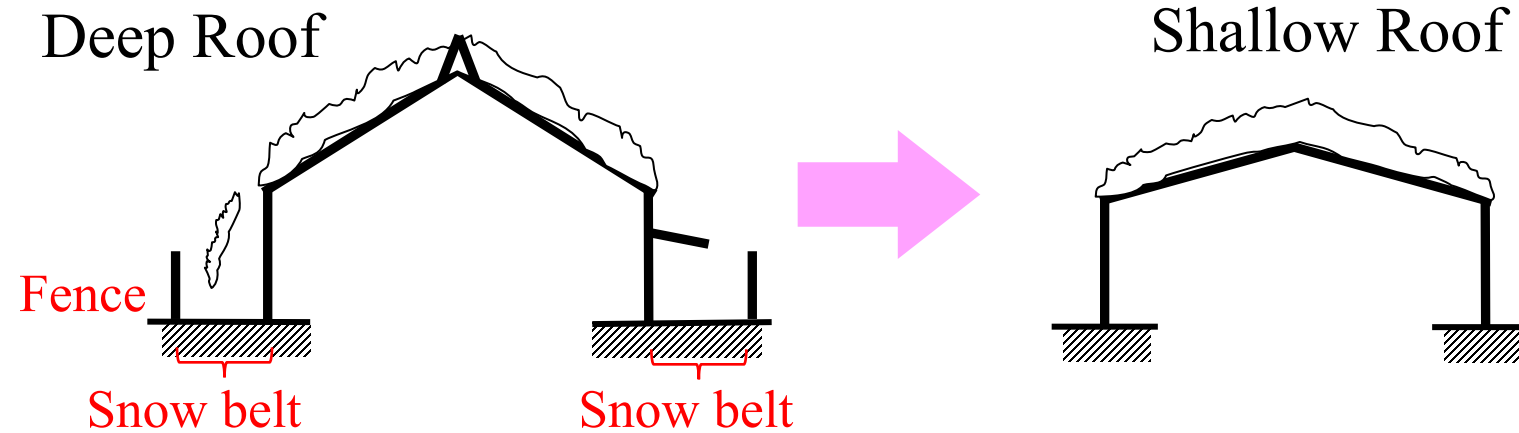
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Catastrophic collapse of Spatial Structures by Heavy Snow in Japan

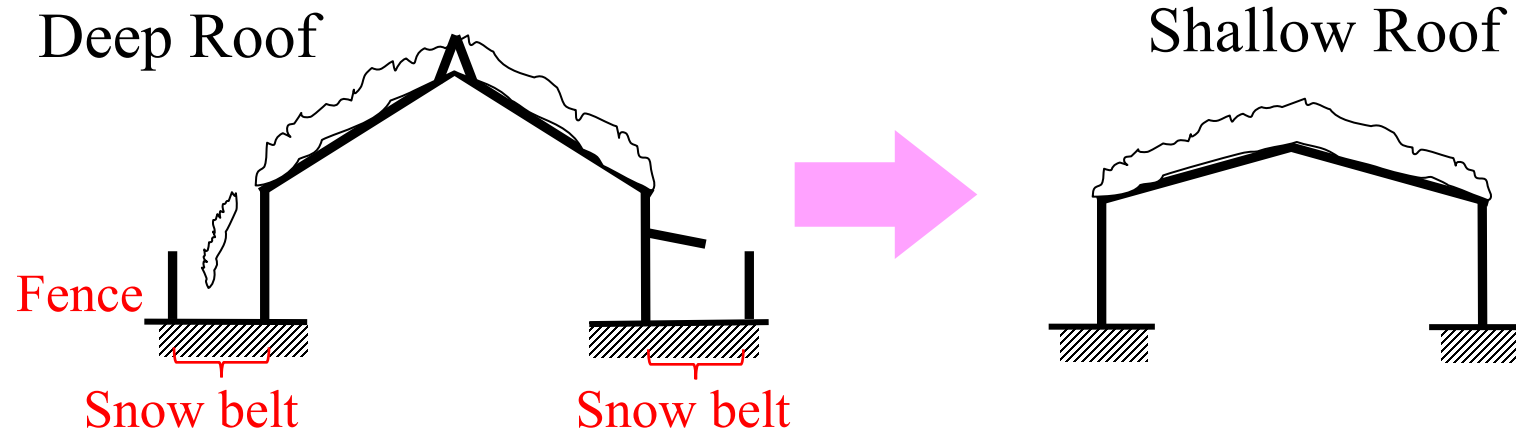


How to Prevent Catastrophic Failure



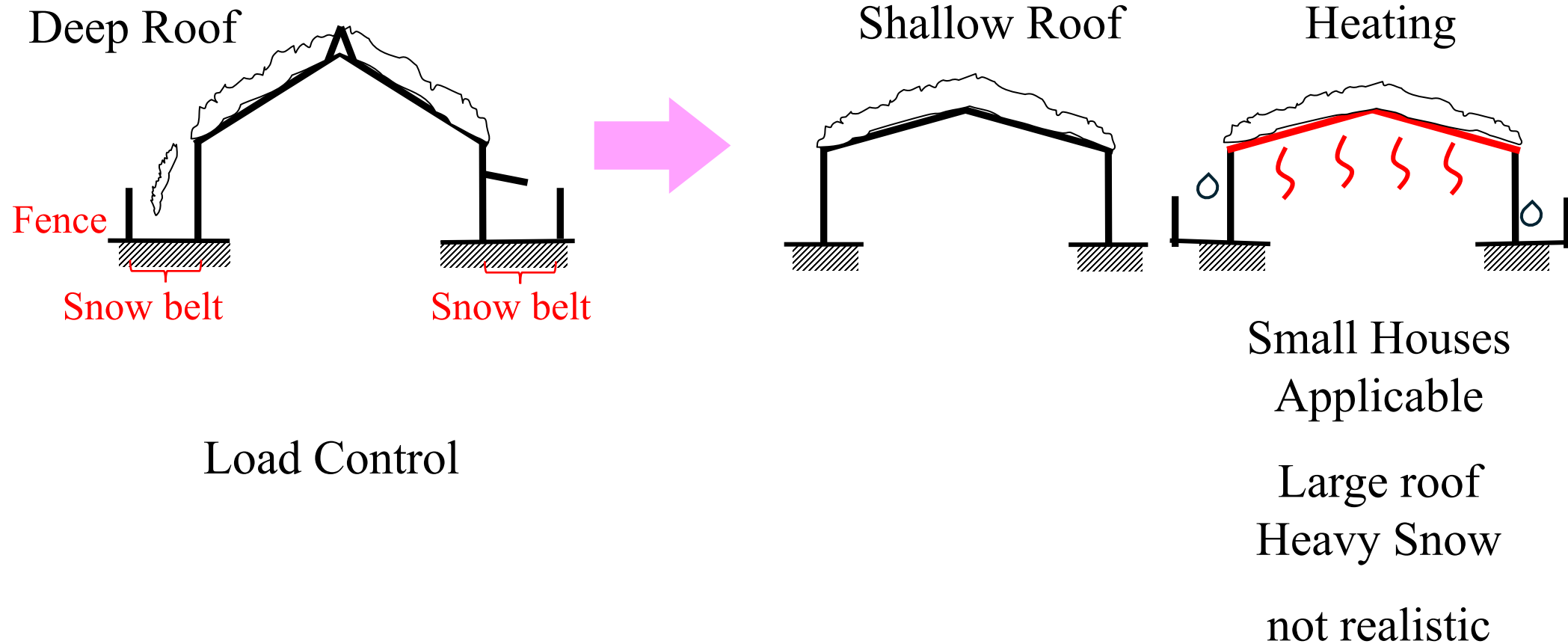
Load Control

How to Prevent Catastrophic Failure

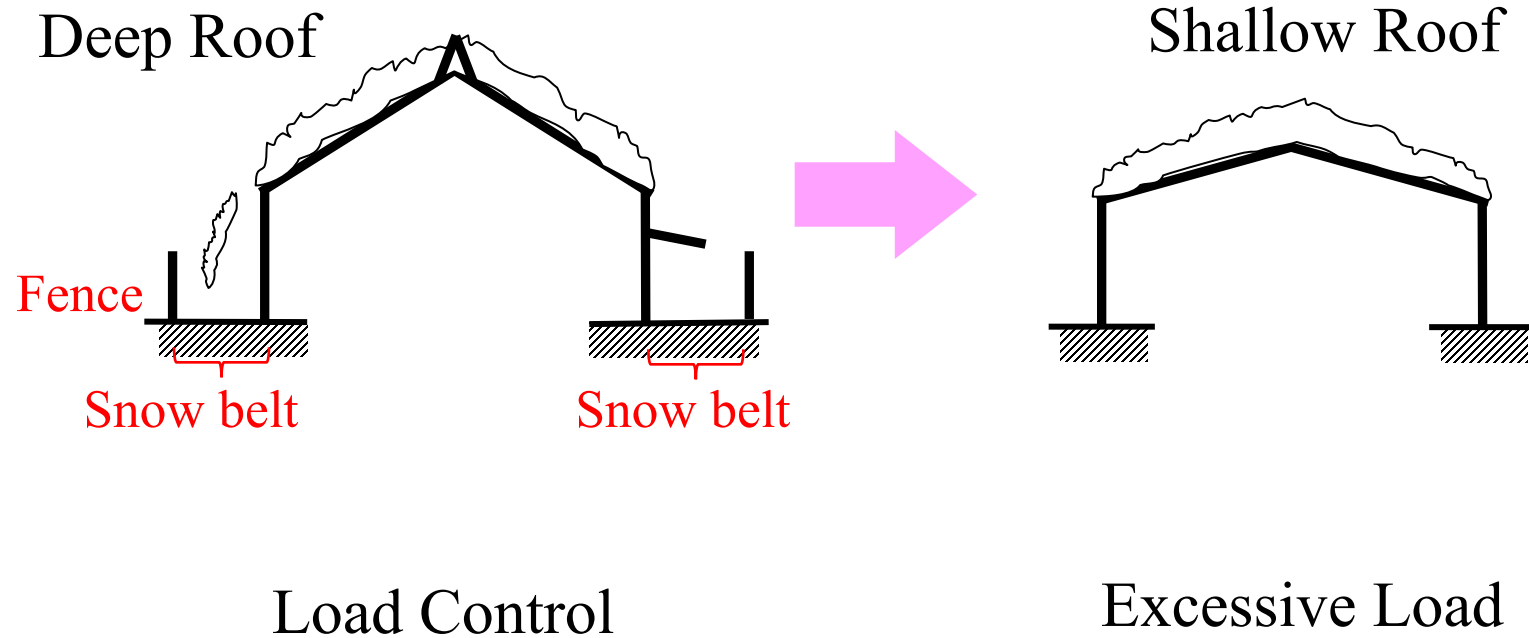


Load Control

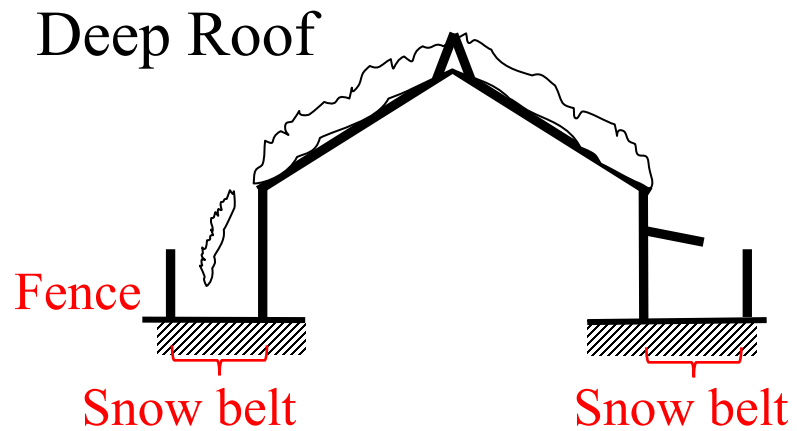
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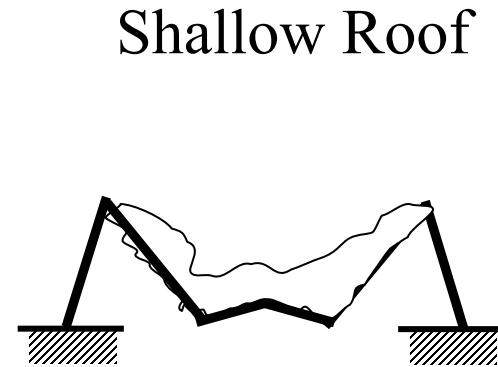
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How to Prevent Catastrophic Failure

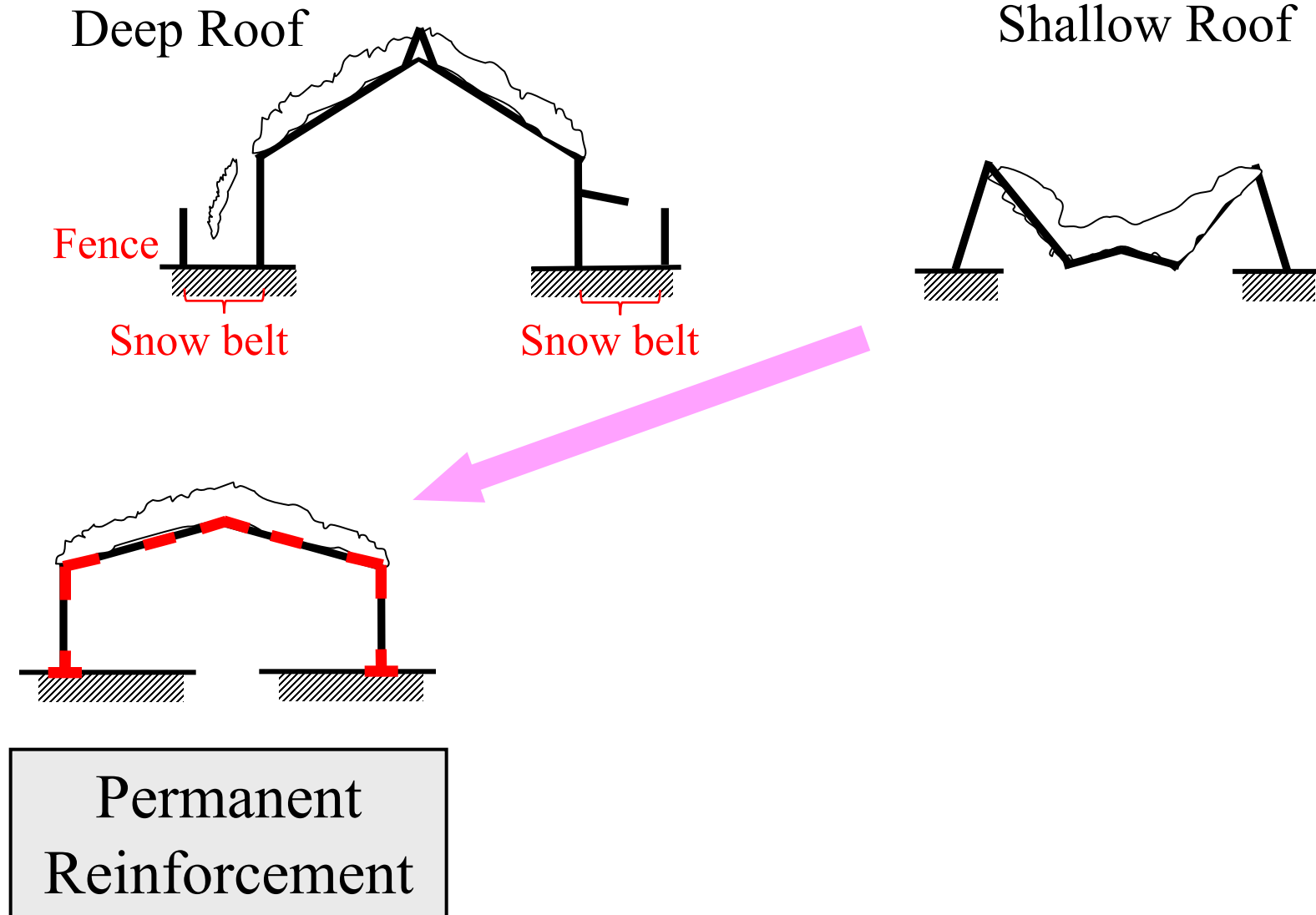


Load Control

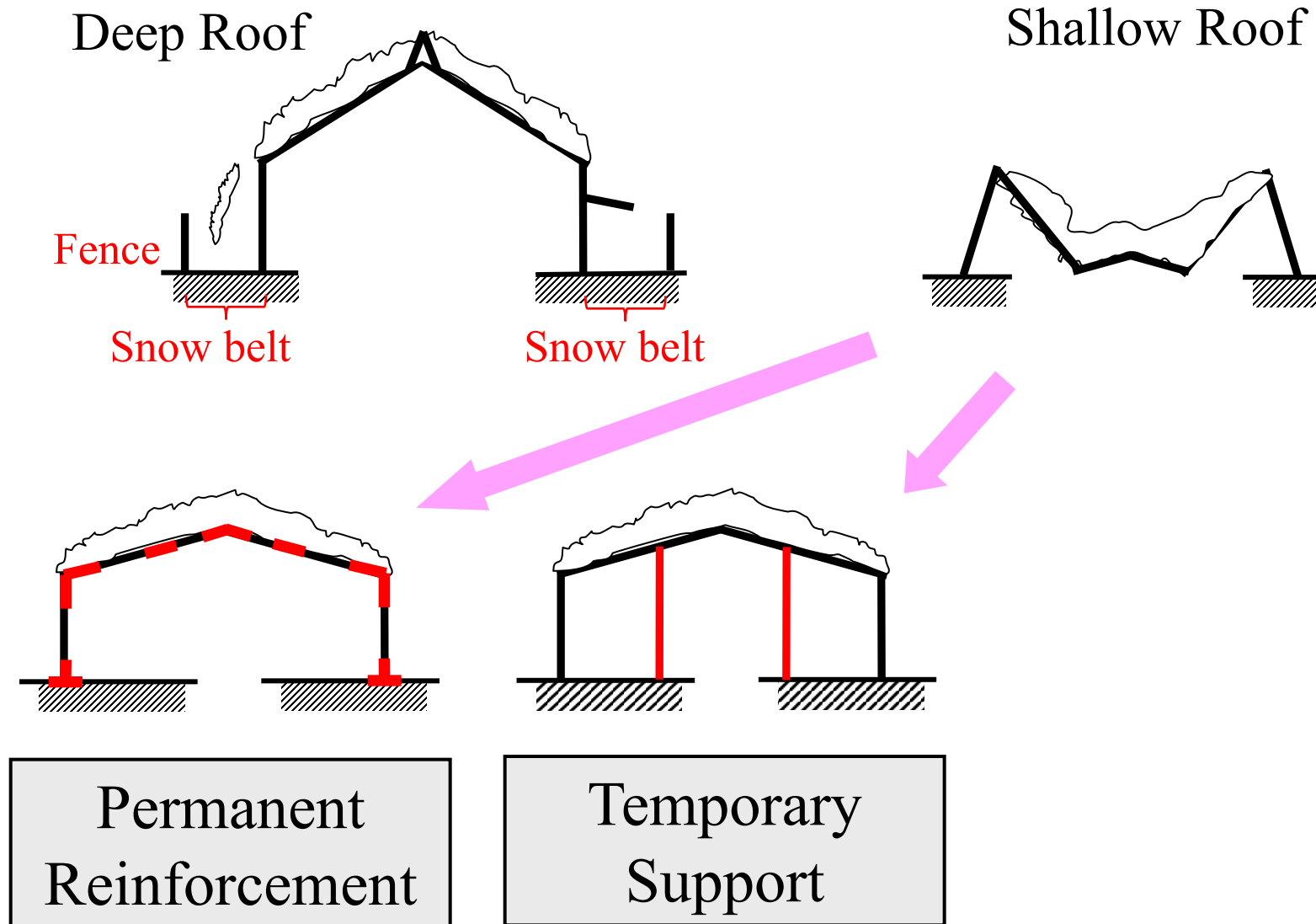


Excessive Load

How to Prevent Catastrophic Failure



How to Prevent Catastrophic Failure



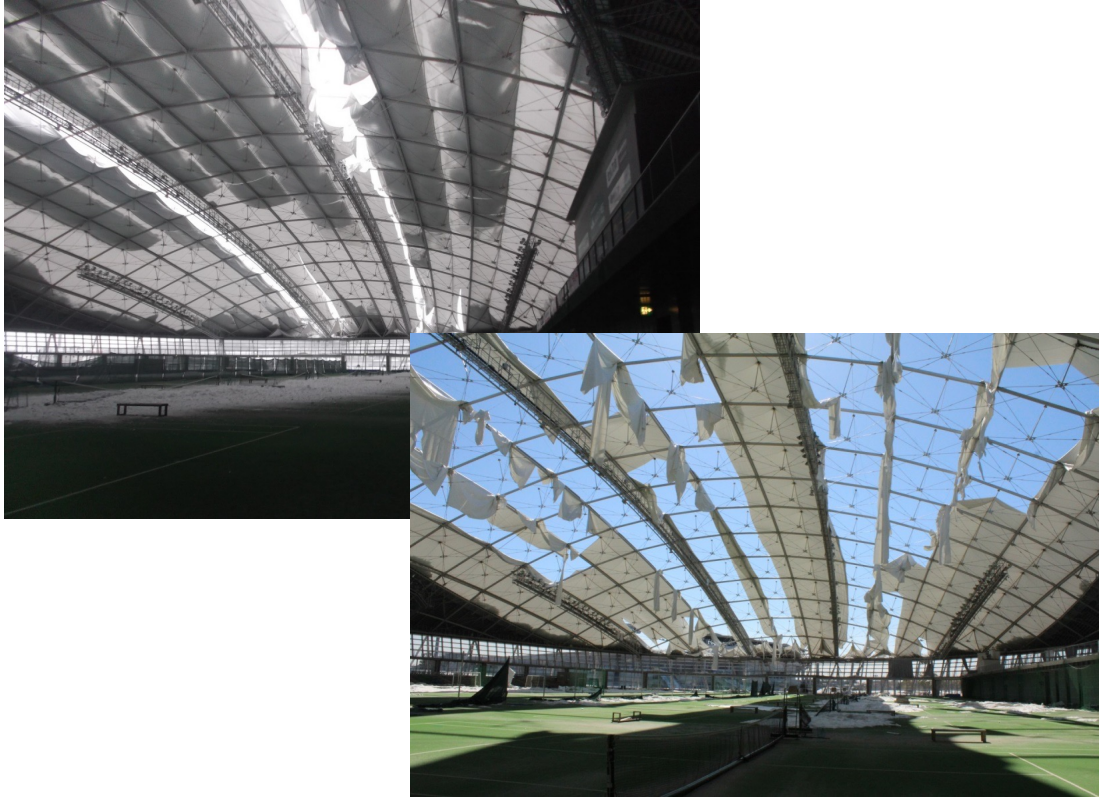
Spatial Structure Damage, by Heavy Snow in Japan Feb.2014,



Spatial Structure Damage, by Heavy Snow in Japan Feb.2014,



Spatial Structure Damage, by Heavy Snow in Japan Feb.2014,



Claddings Failed
Slow Progress
Enough time for evacuation



Catastrophic collapse in 1 second
-> No time for evacuation



Failure of claddings before the collapse of skeleton

→ Force limiter

Heavy Snow (including rain after snow)

Lessons to better structural design

How strong structures should be?

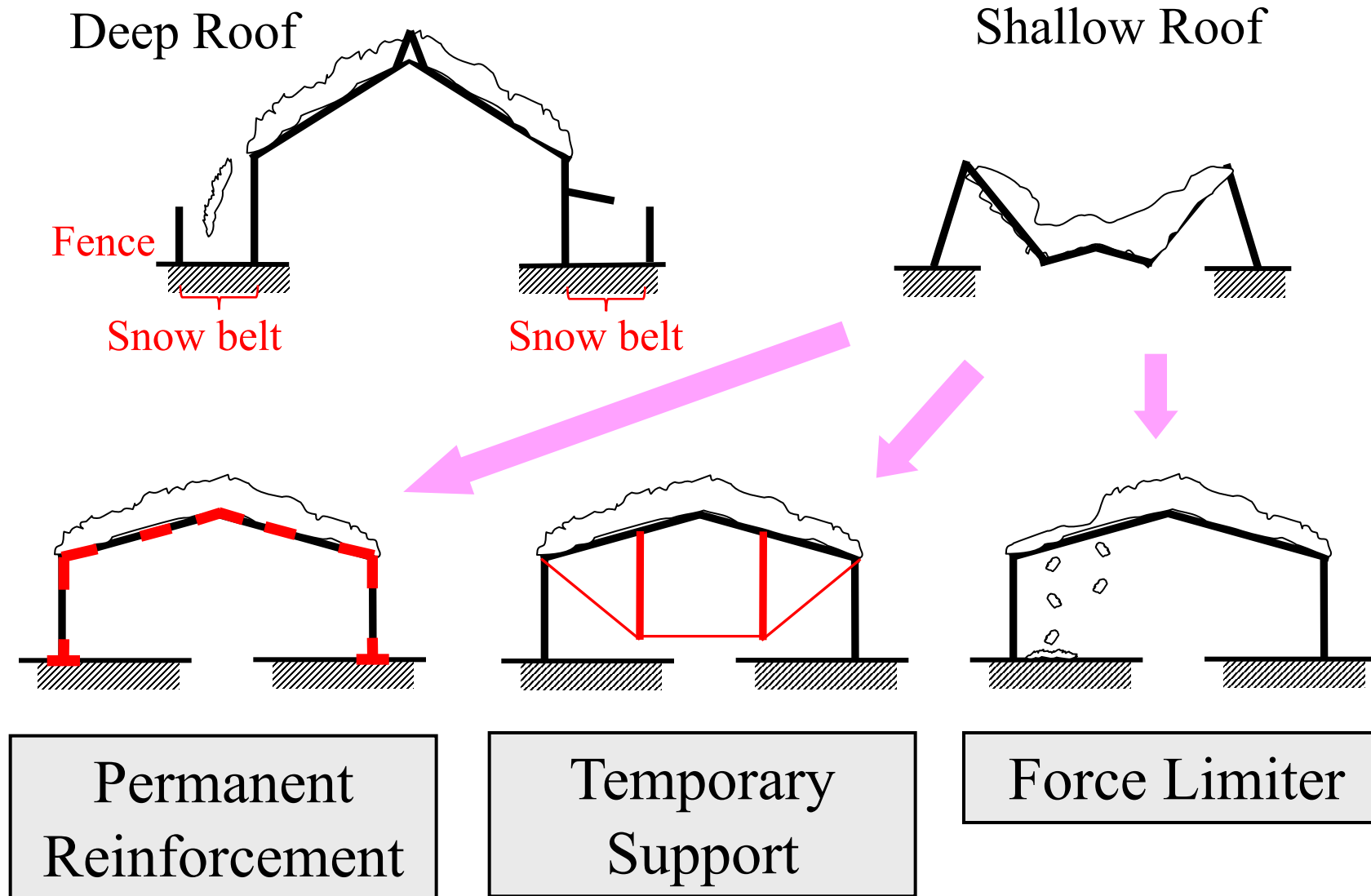
Unpredictable design load of Natural phenomena

We can control the load

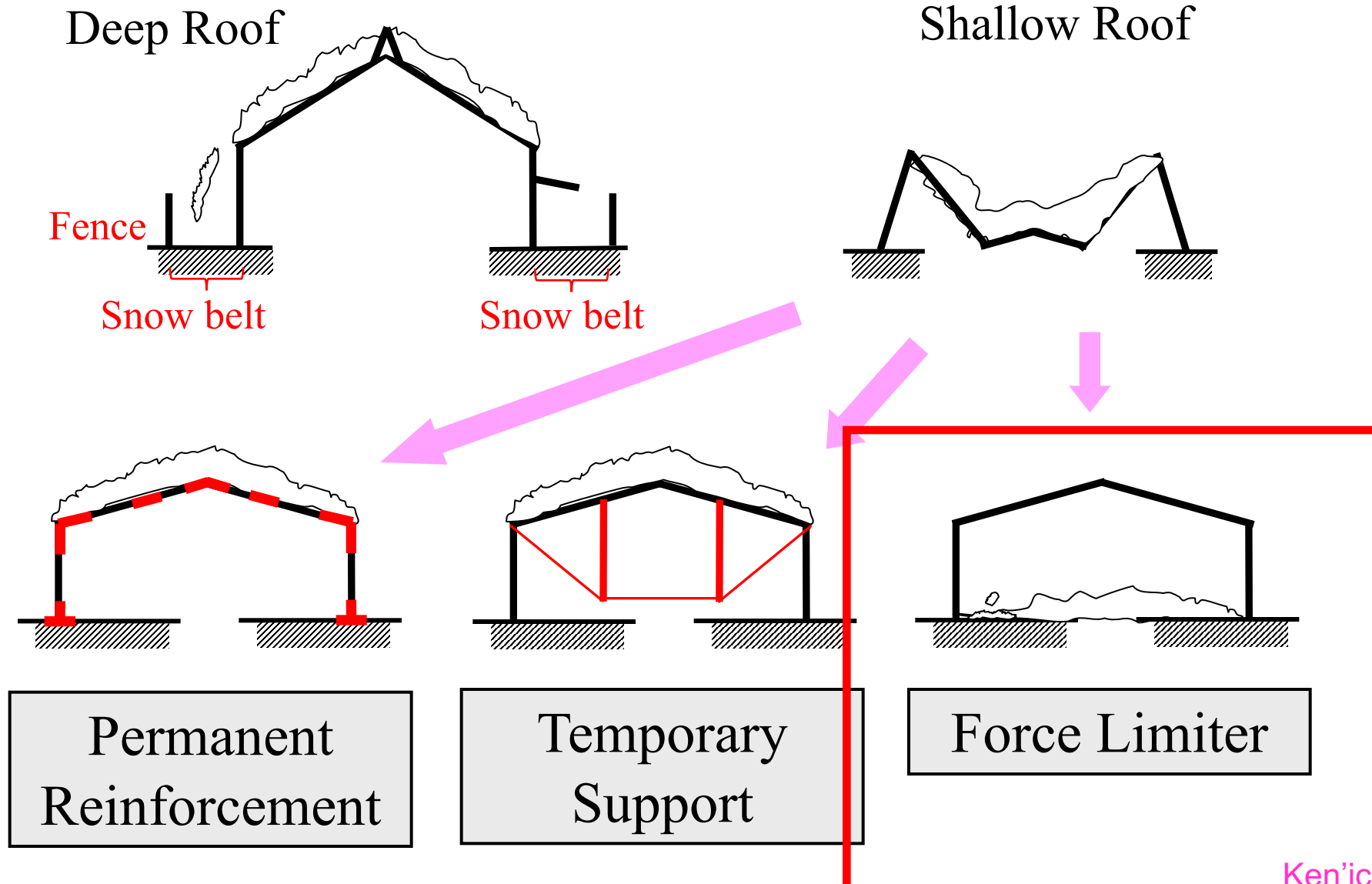
Main Structure < Claddings -> Catastrophic collapse

Main Structure > Claddings -> Warning for evacuation, partial failure
Preserving the main structure

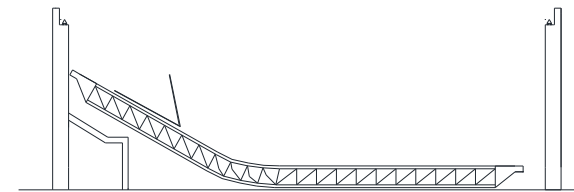
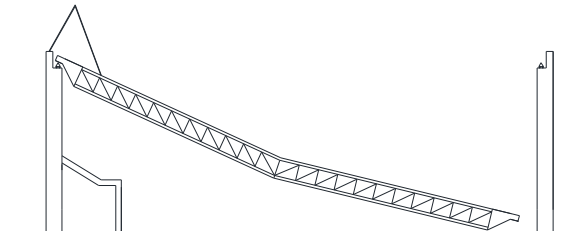
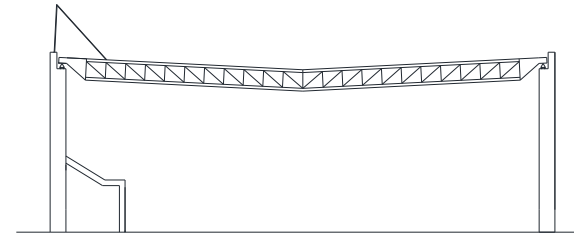
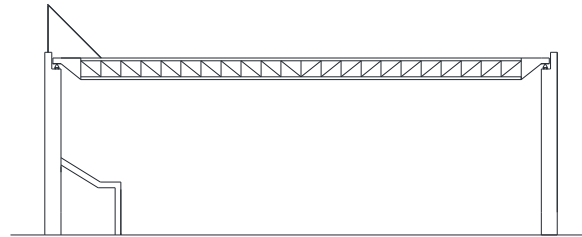
How to Prevent Catastrophic Failure



How to Prevent Catastrophic Failure

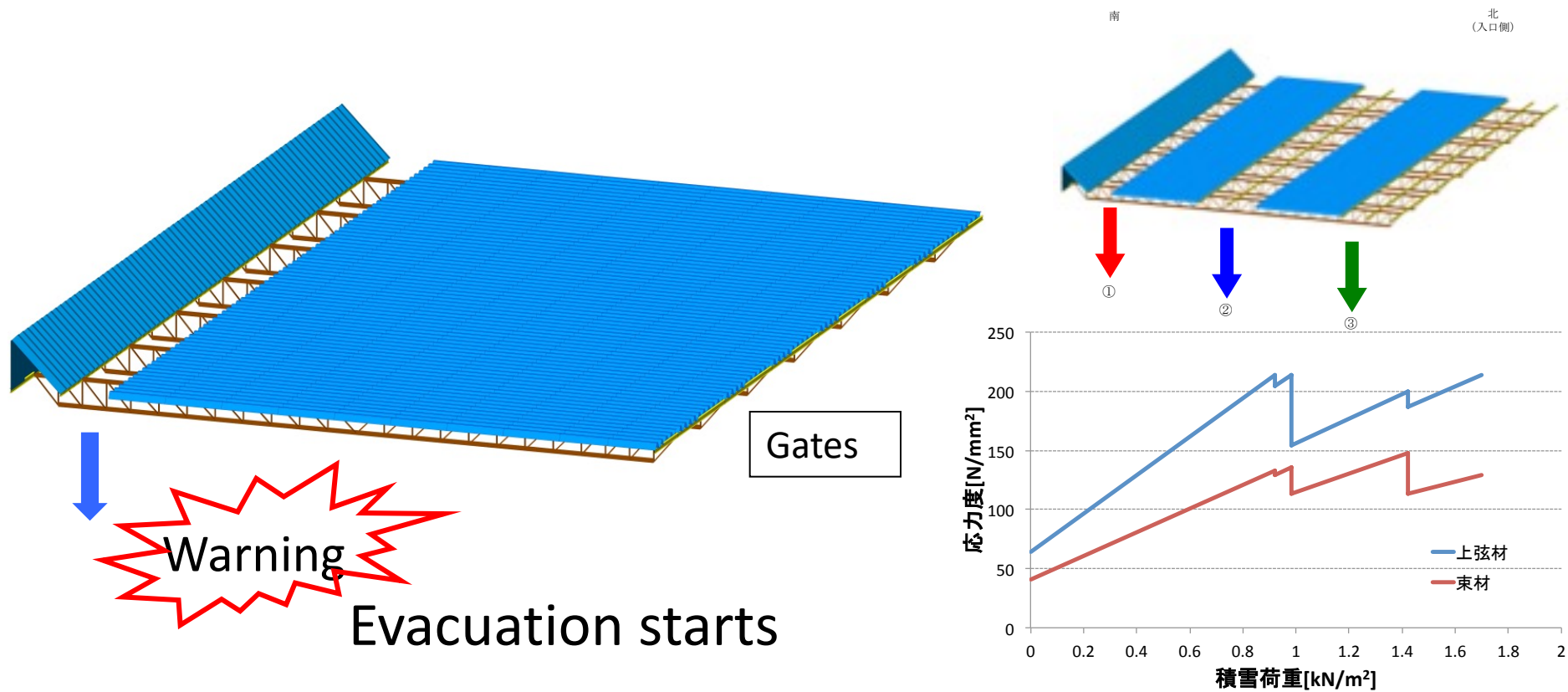


How to Prevent Catastrophic Failure



Buckling of a compression member

Weaker Roof Cladding as Force Limiter



Time for evacuation and better reparability

Failure of Non-Structural Components Life-Safety and Business Continuity

Development of Earthquake Resistant Design of Structures

- Structural Failure -> Reduced
- Non-Structural Components -> Danger of Suspended Ceilings became clear

Disturbance

- Main load is not earthquake
- Gravity load and Human Tolerance should be well considered

Jan.1st, 2024, Noto Earthquake,



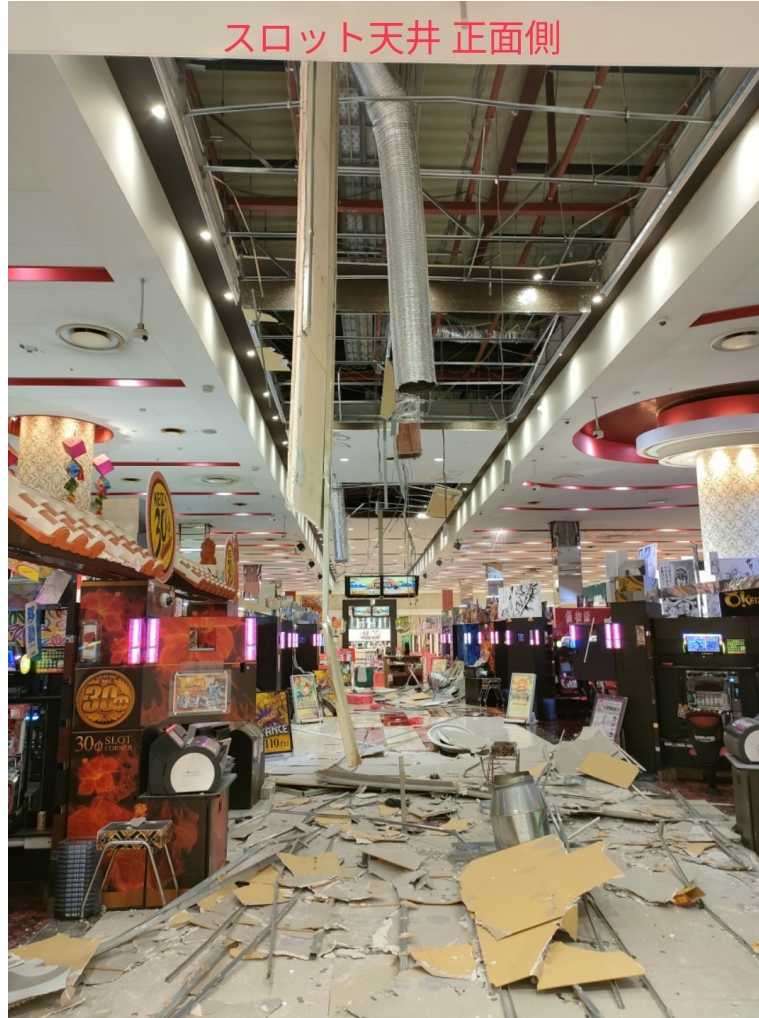
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Damage to Suspended Ceilings



A Slot Machine House
Structurally Intact (no-damage)



Suspended Ceilings in a Slot Machine House



Glass Ceilings in Kanazawa 21st Museum

Damage to Suspended Ceilings



Structurally Intact



Suspended Ceilings in a Public Gymnasium

Ken'ichi Kawaguchi, IASS

April 17, 2024, Bungo-Suido Earthquake, M6.6



Suspended Ceilings in a Public Hall

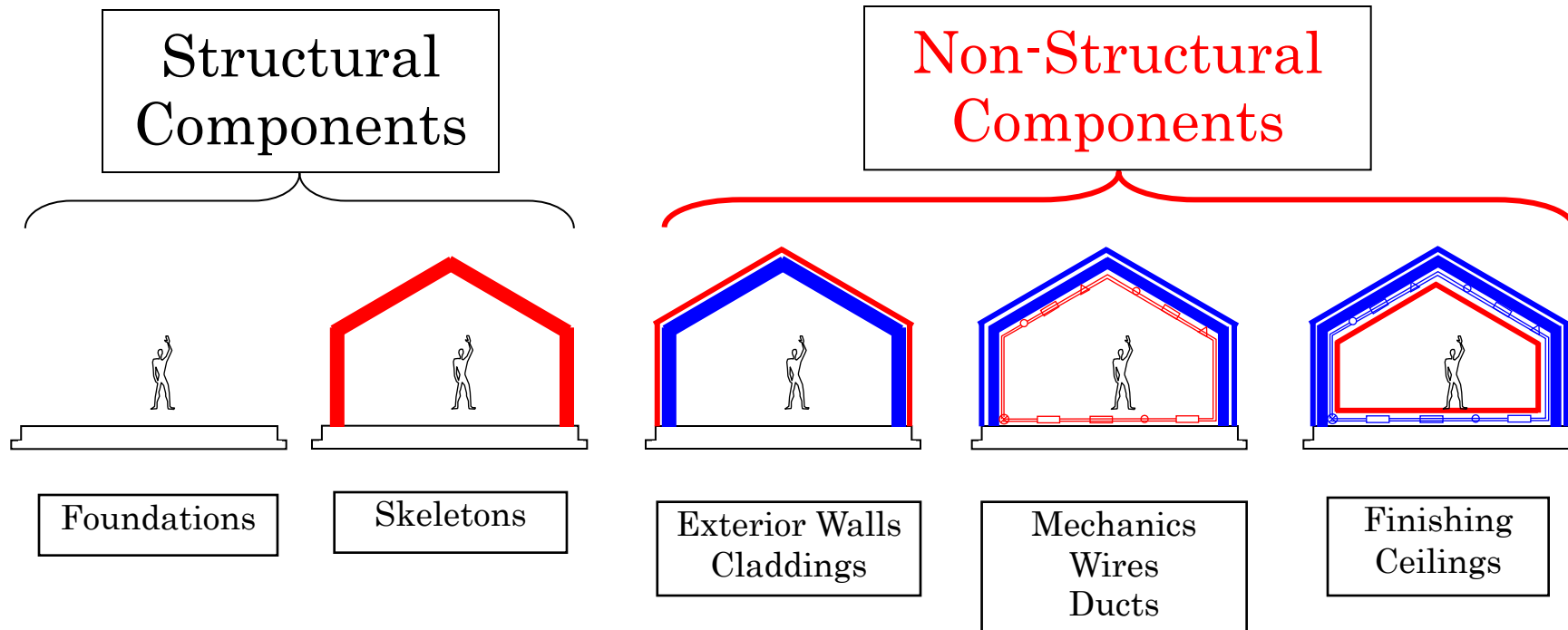
Security Video Record



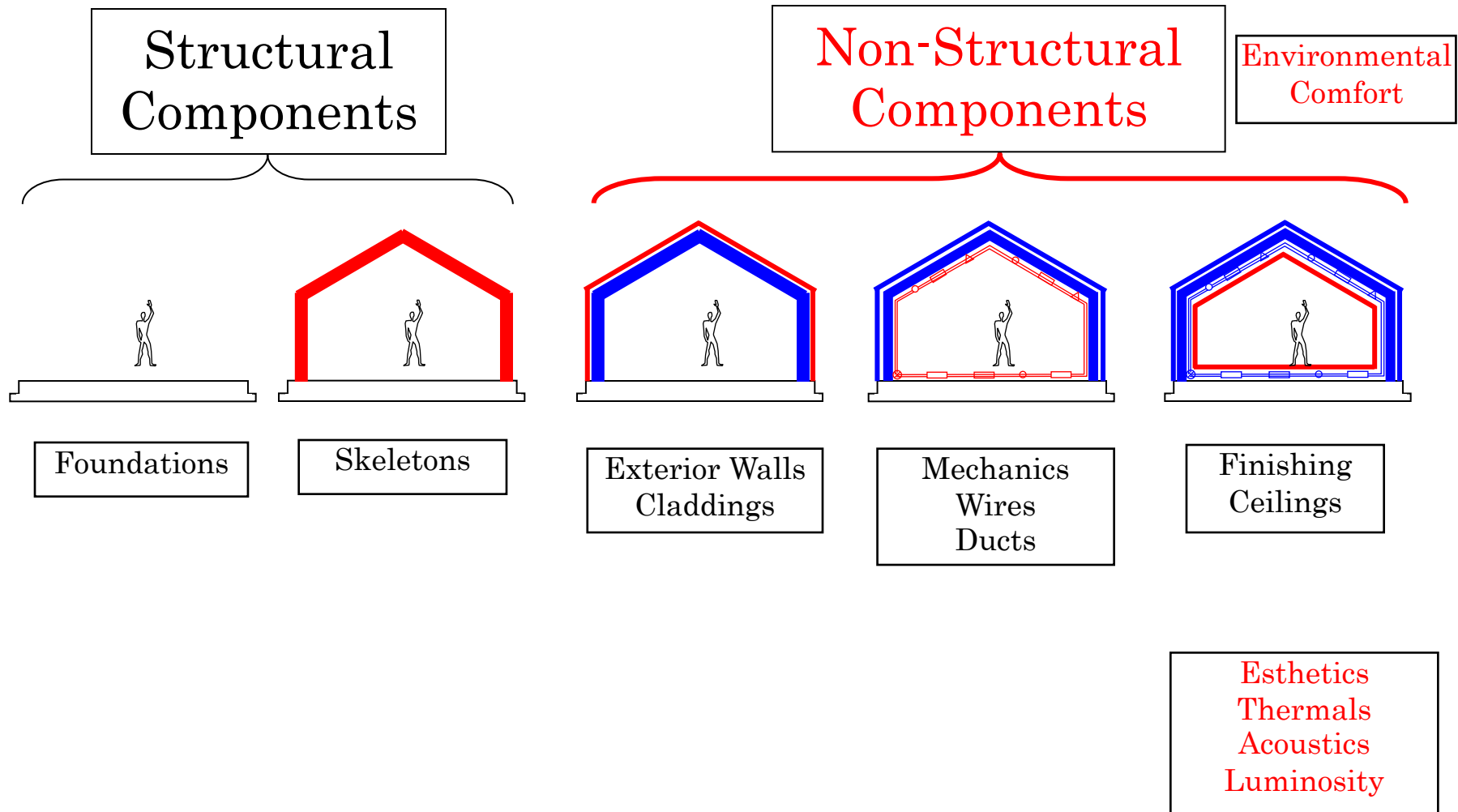
Swimming Pool at Sendai, 2005

K. Kawaguchi

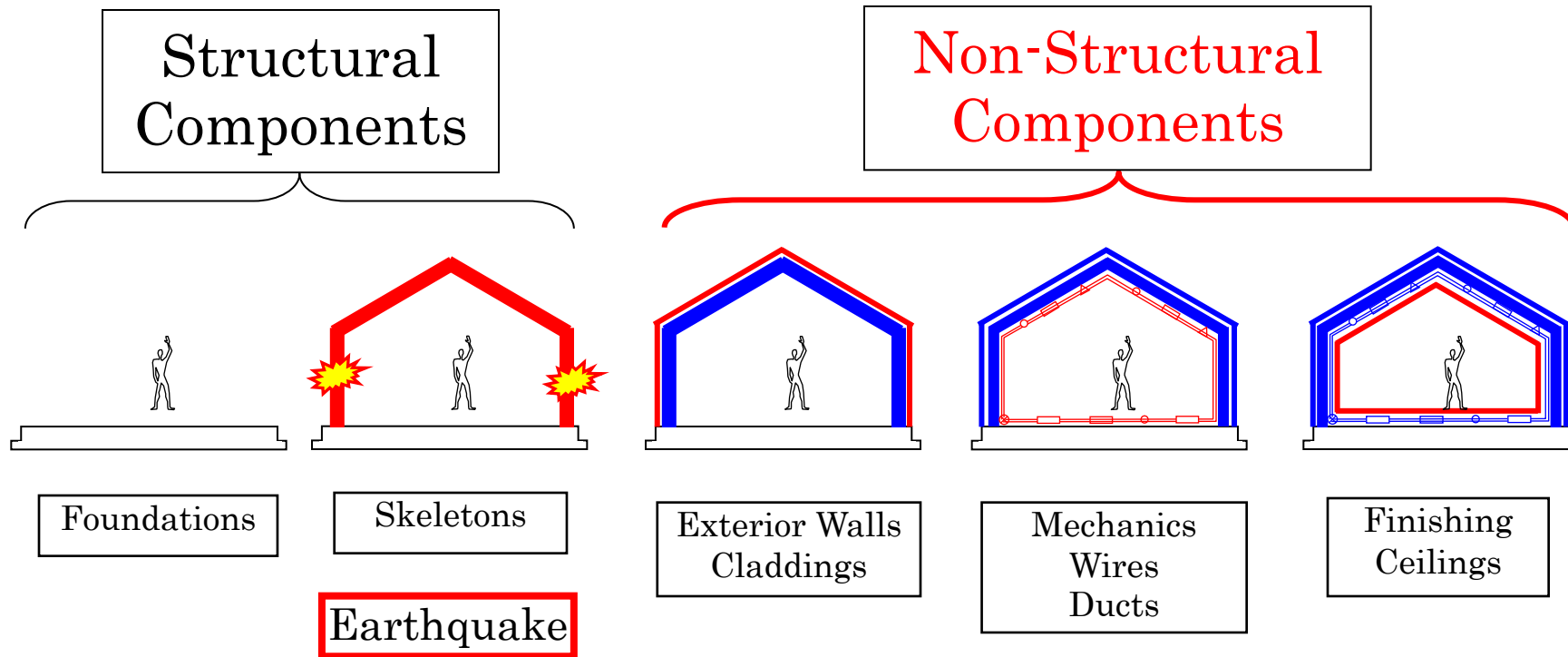
Building Components and Construction Process



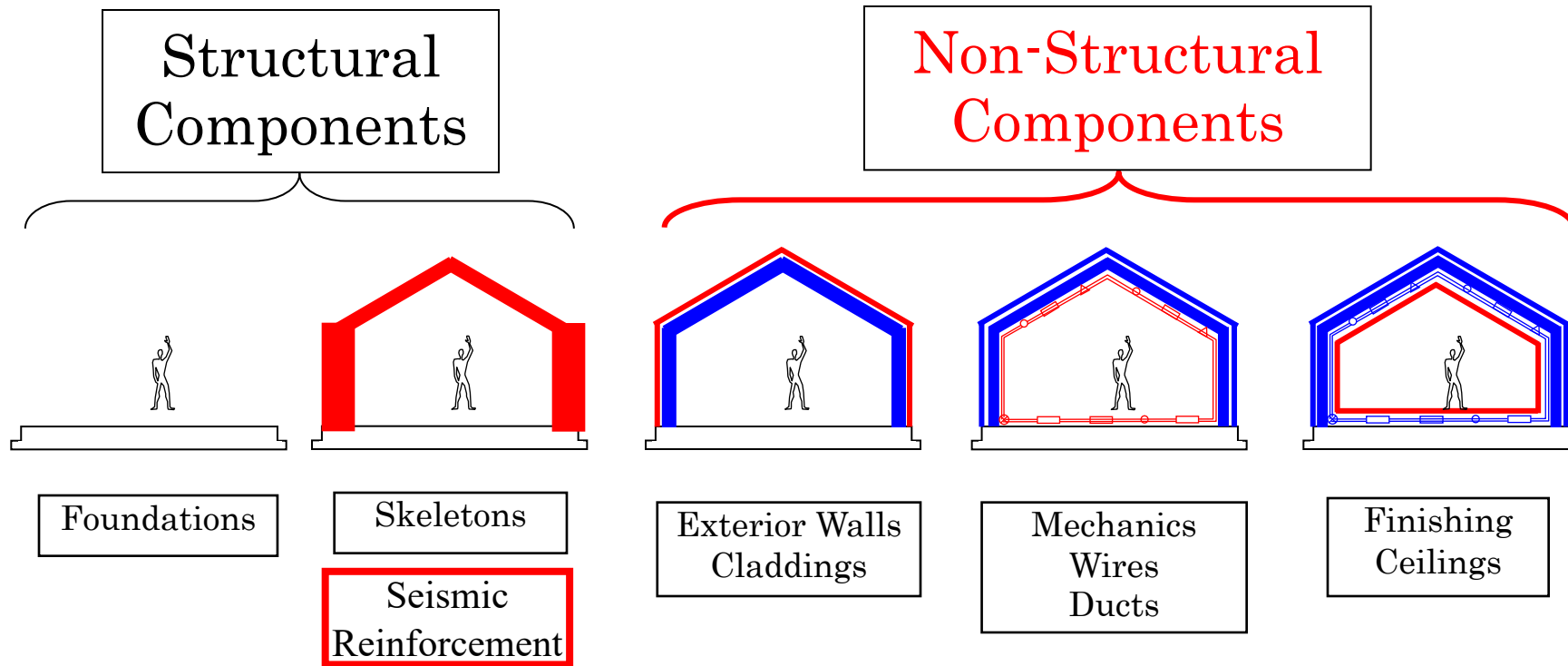
Building Components and Construction Process



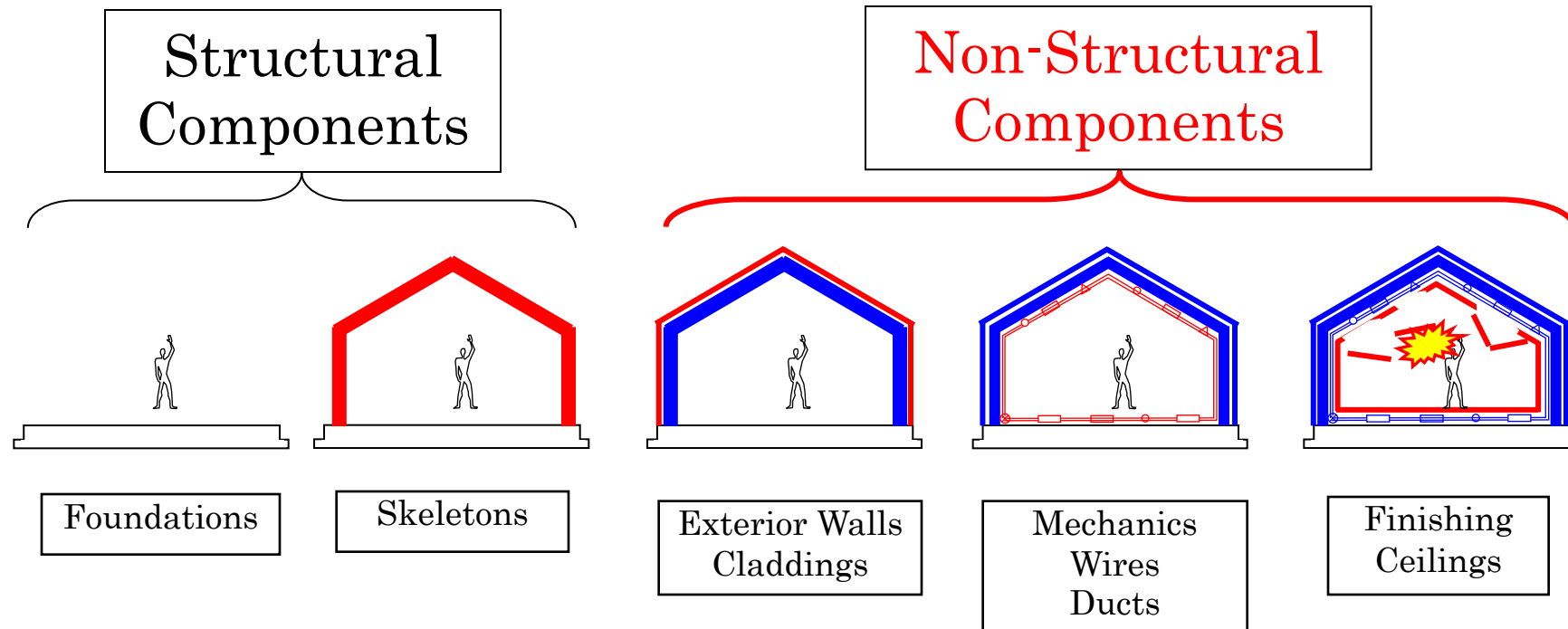
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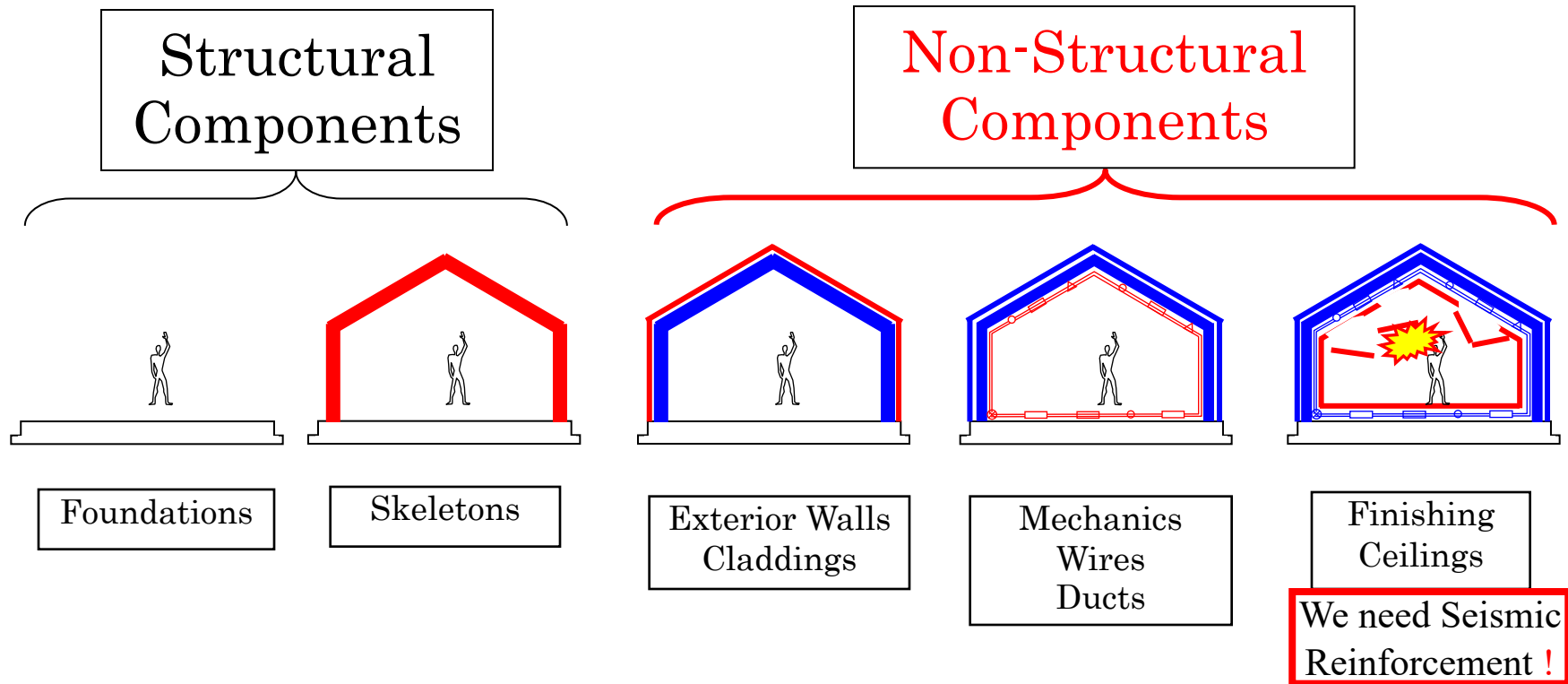
Building Components and Construction Process



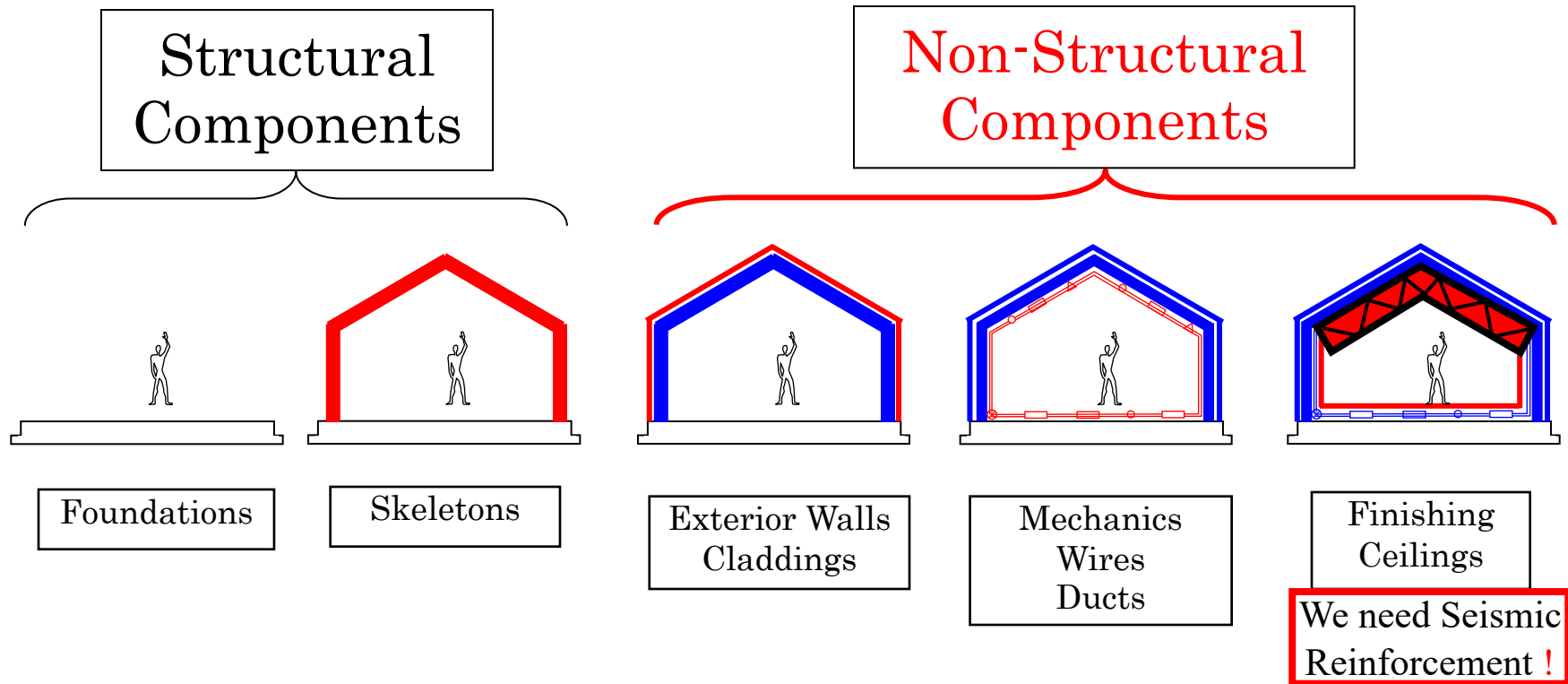
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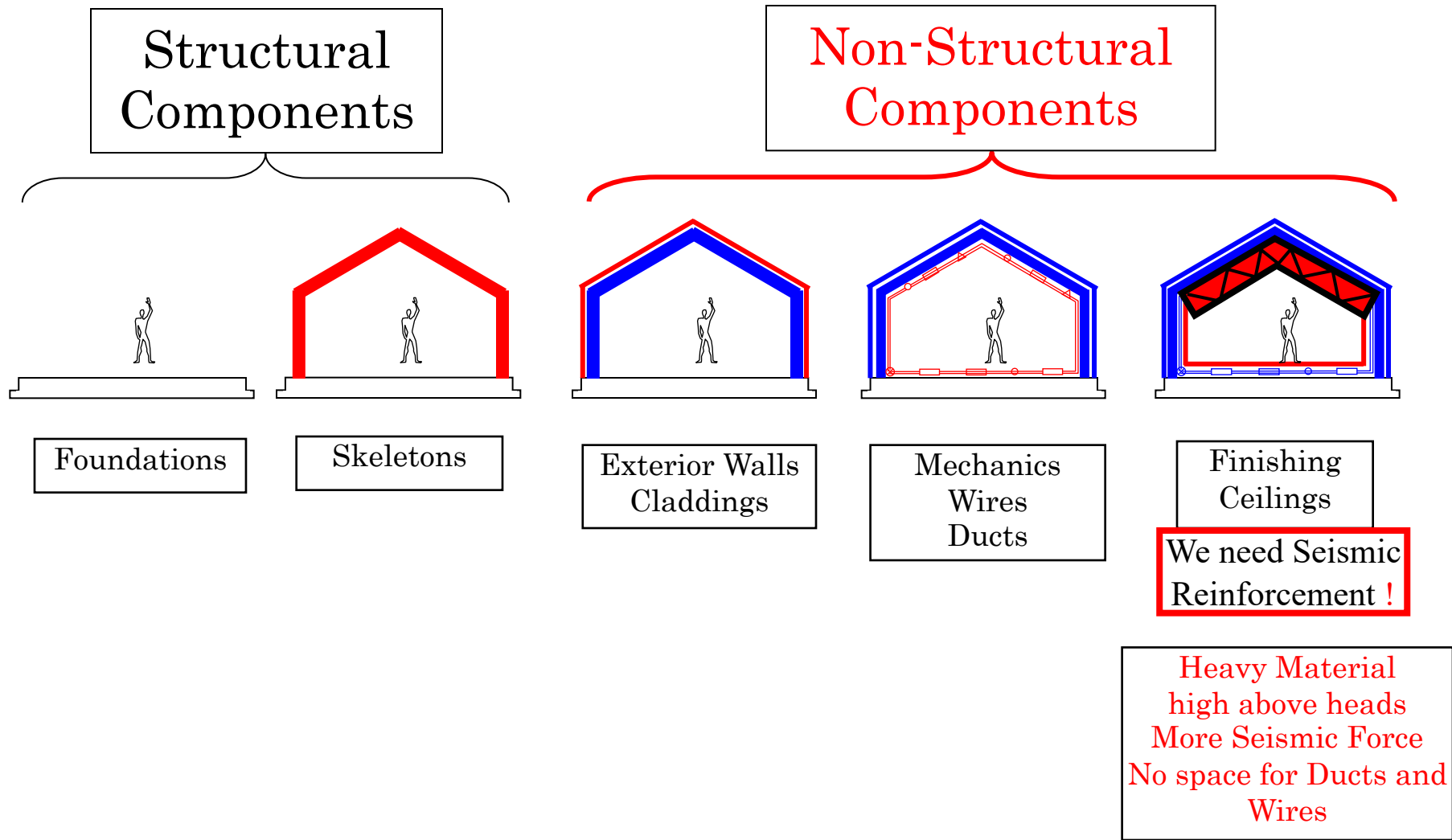
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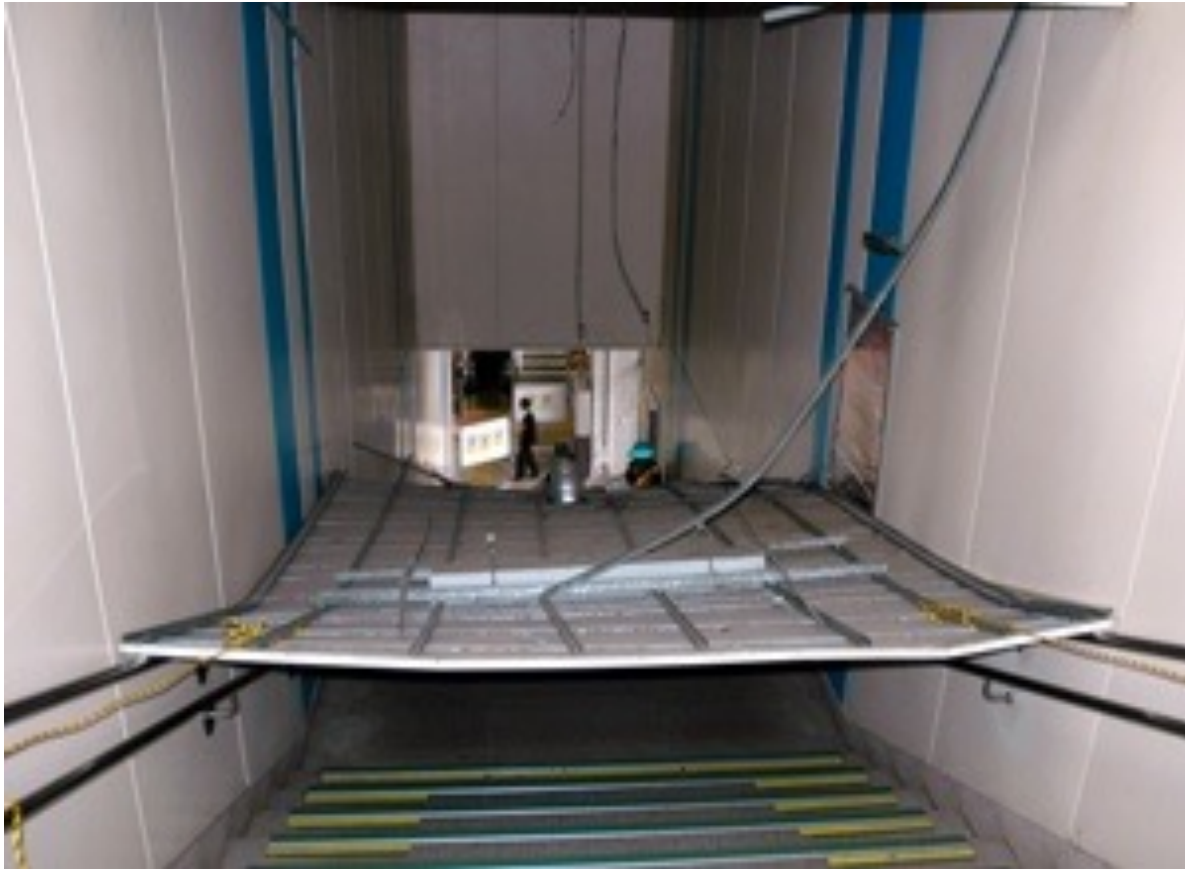
Building Components and Construction Process



Building Components and Construction Process



Ceiling Failure without Earthquake



Ceiling fall in a stair case, Oct.2011



Ceiling fall in a swimming pool, July 2013

Sudden Collapse of Ceiling in London



(image from YouTube)

Apollo Theater London, Dec.20, 2013



80 people were injured (images are from websites)

Shanghai, Aug.24, 2019



London, Piccadilly Nov.06, 2019



London, Piccadilly Theater, Nov.06, 2019, BBC_News Japan_109554299_hole

Ken'ichi Kawaguchi, IASS

Accidental Ceiling Fall

Gravity is the main force.
Safety is assessed by impact to
users.

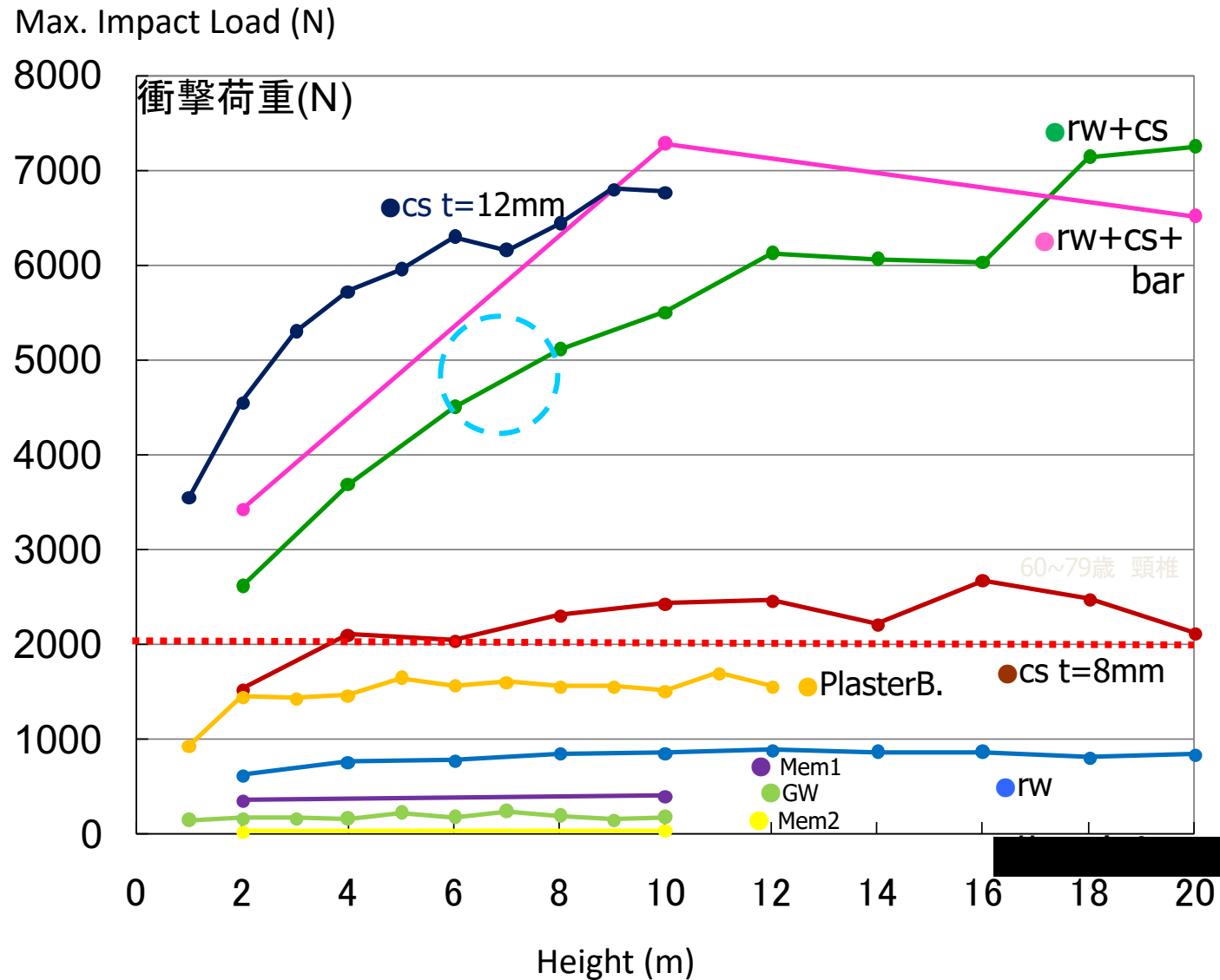
Human tolerance.

Head bone (skull)

Safety of Ceilings in Large Rooms



Safety Assessment by Human Tolerance



Real injury



Fracture Load of
Parietal Bone
(Nahum)

2000N

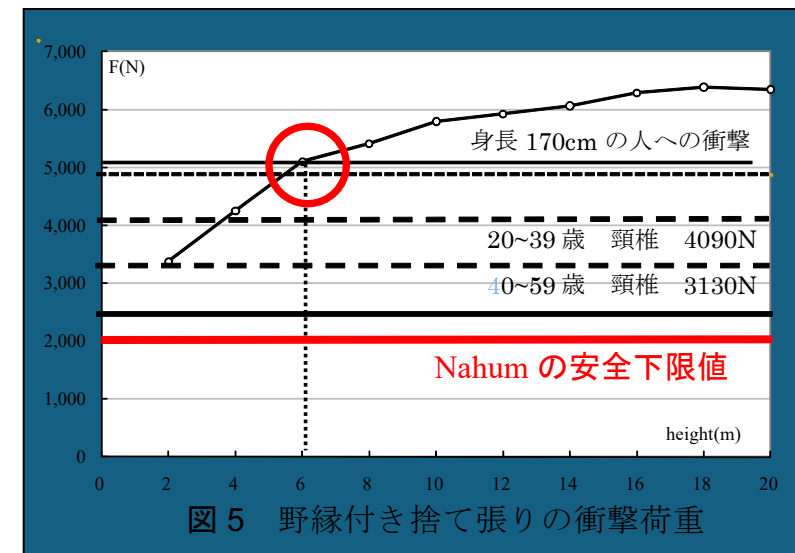
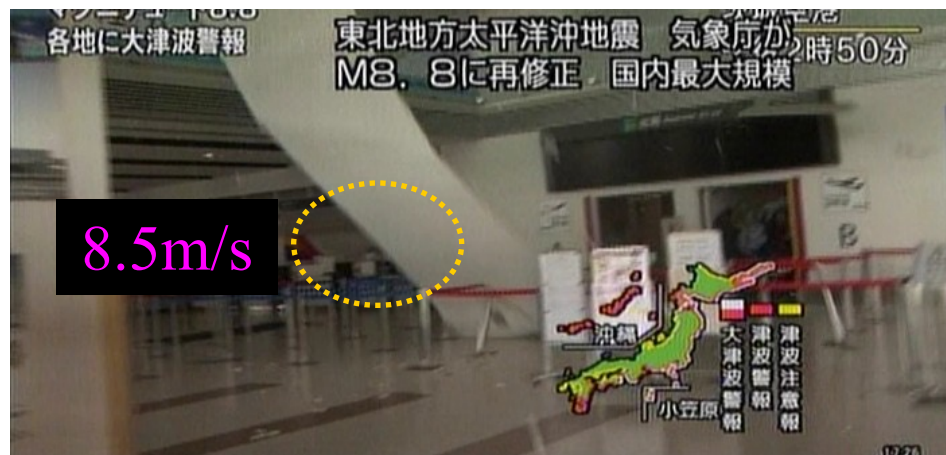
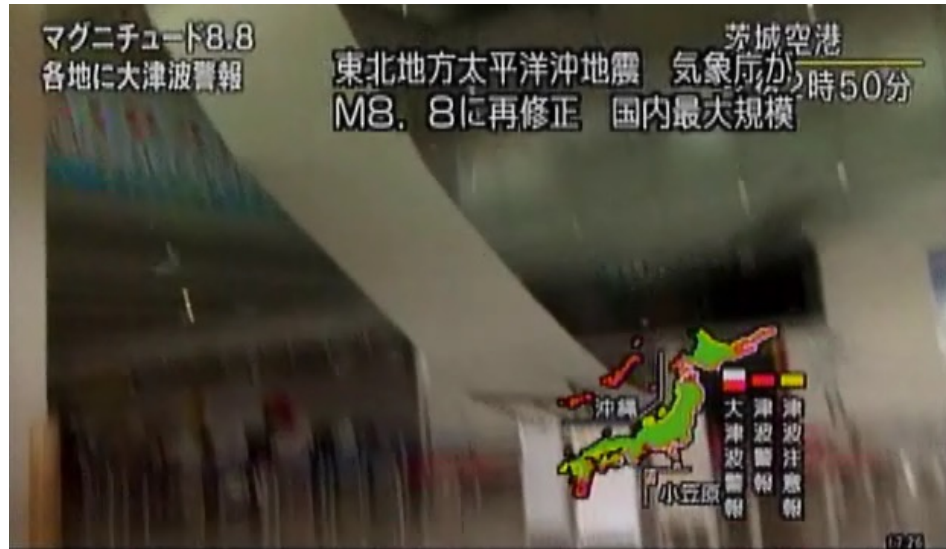
K. Kawaguchi

Entrance Hall of Ibaraki Airport, Mar.11, 2011

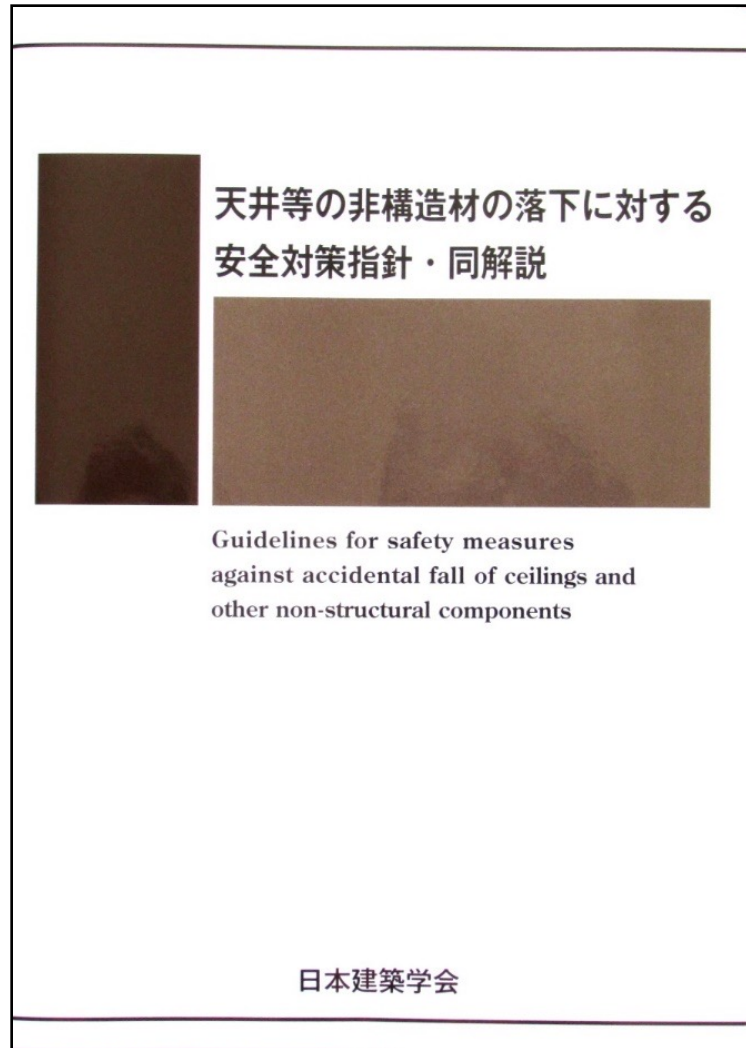


お問い合わせ デジサポ助成金相談窓口 0570-093-724(平日9時~18時)

Safety assessment by human tolerance



Guidelines for safety measures against accidental fall of ceilings and other non-structural components



AIJ:
Architectural Institute of Japan

K.Kawaguchi
(Chair)

T.Ikai, T.Ida,
Y.Ozawa, H.Ohta,
K.Muramatsu

N.Kobayakawa

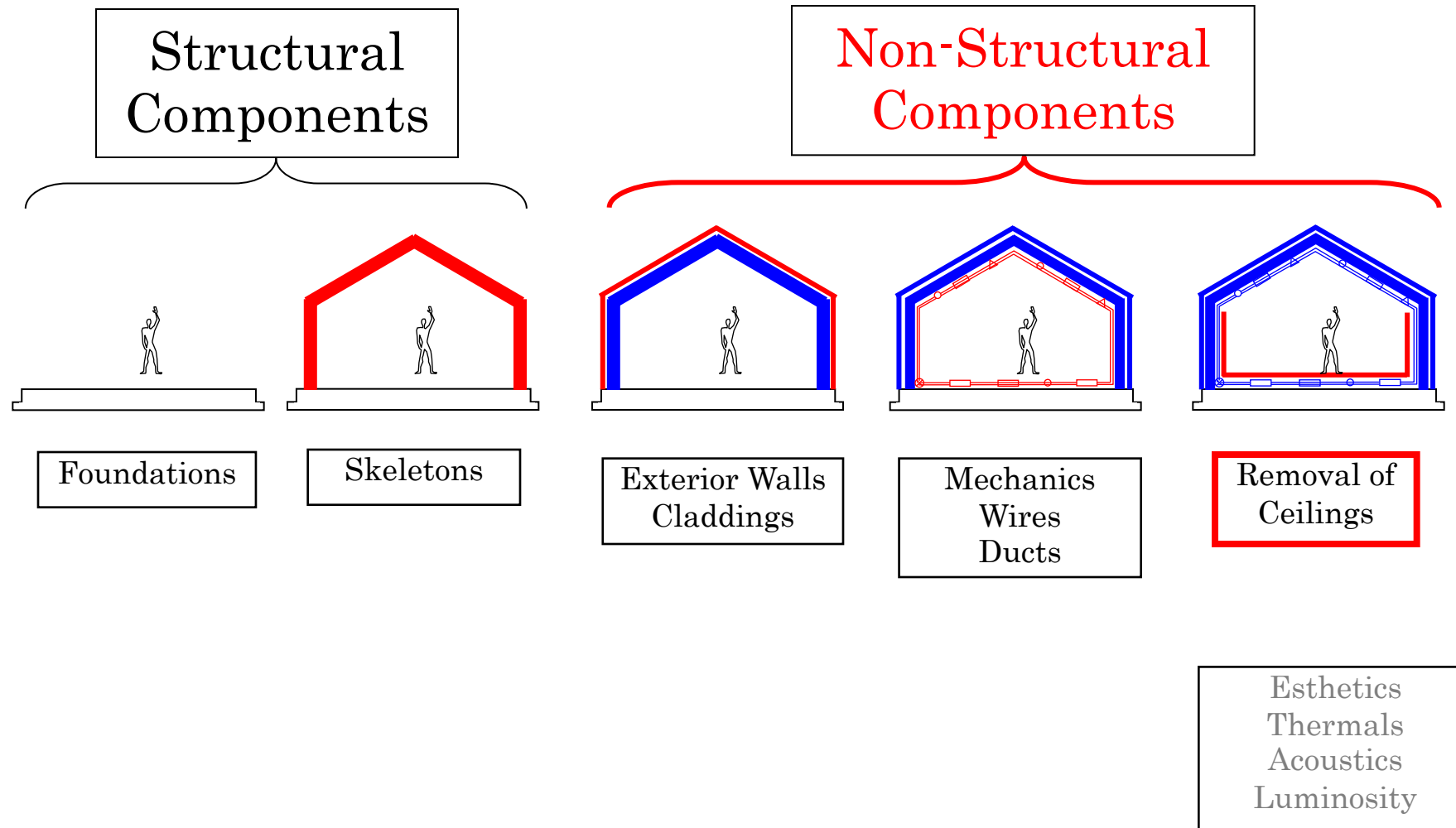
N.Sakuraba,

G.Seike, H.Taga,

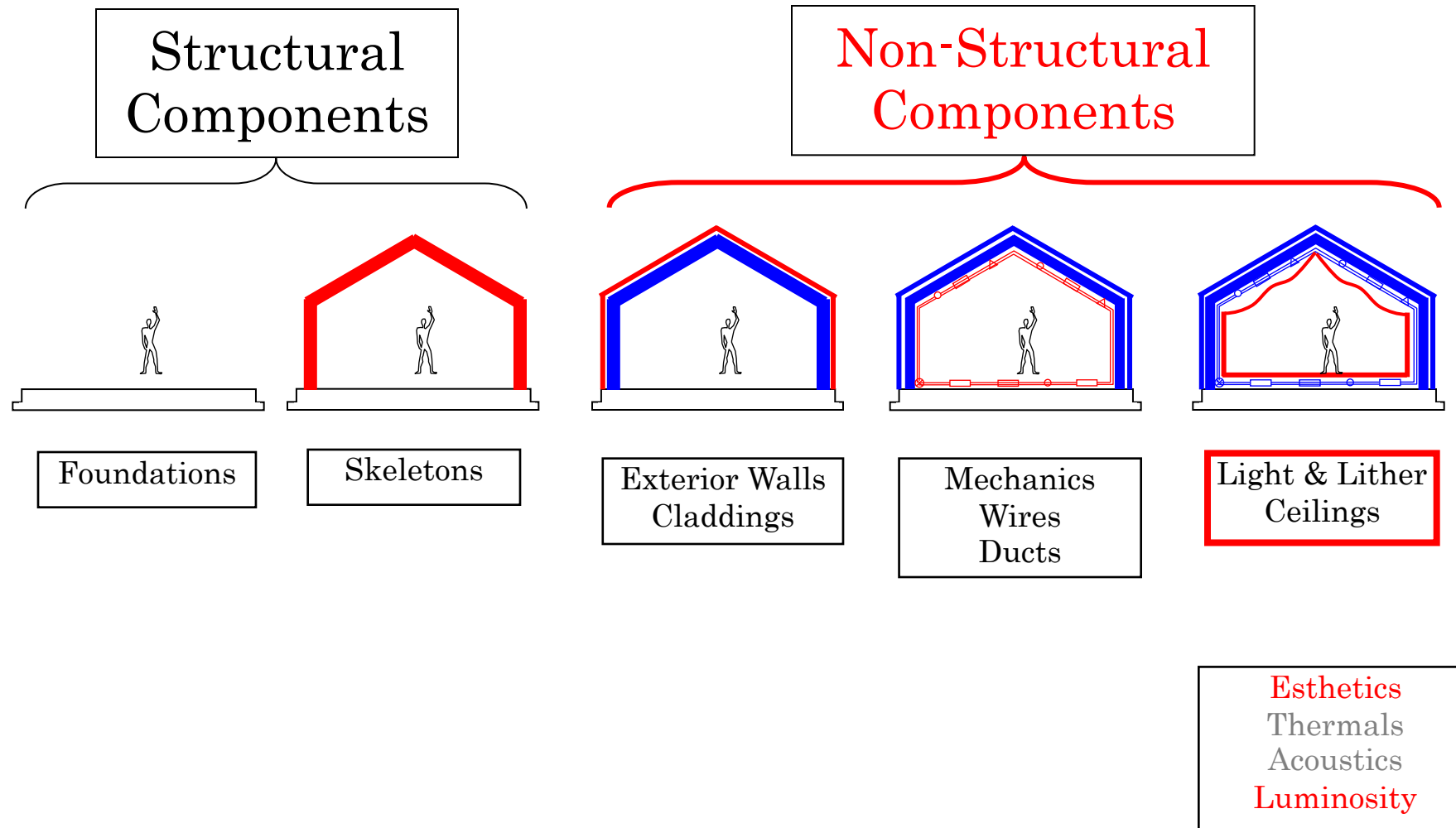
F.Hayakawa

S.Motoyui

No-ceiling (the Simplest measure)

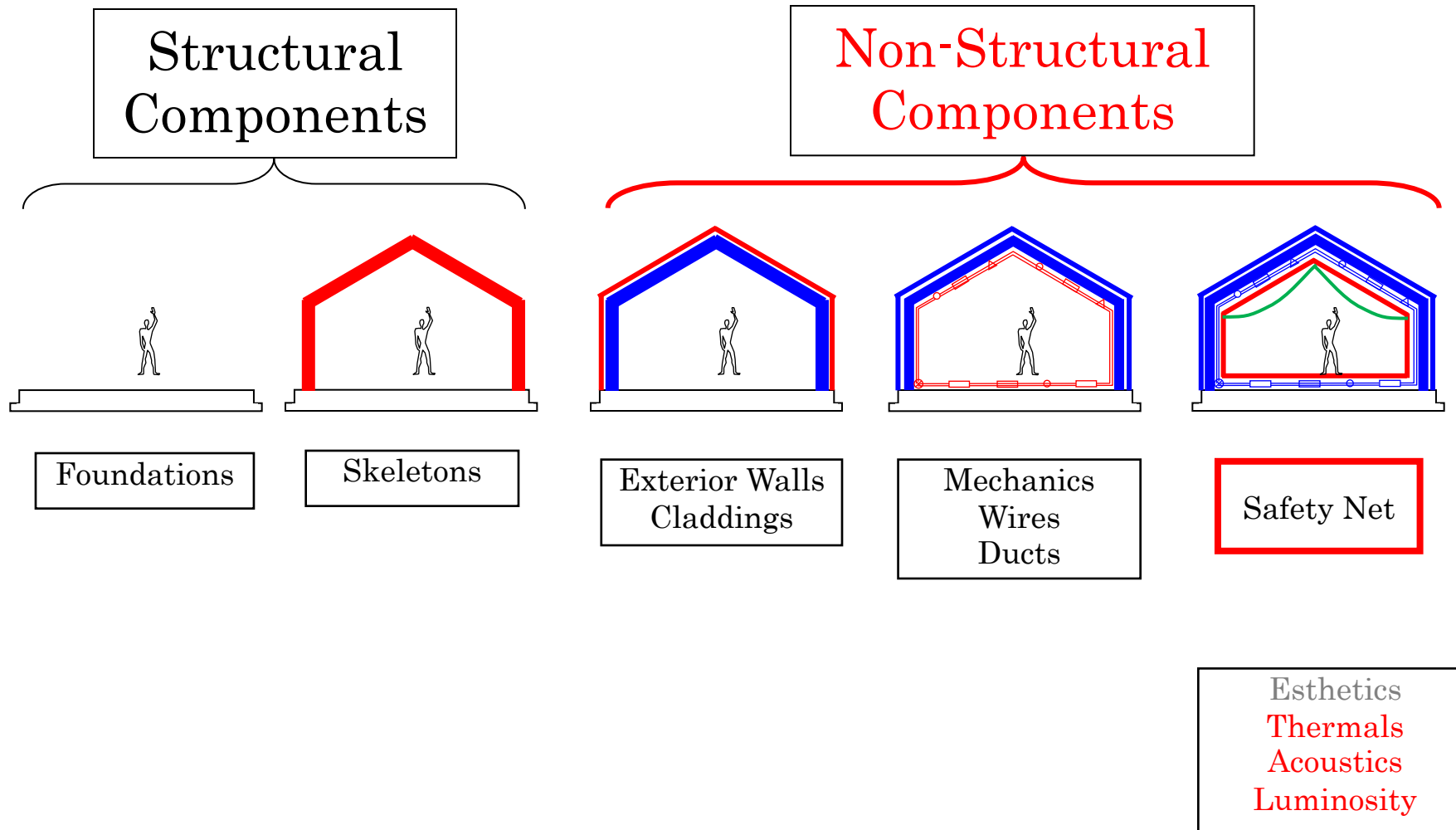


Replacement to Light and Lither ceiling material



Fail-safe system

Safety Net can preserve original ceiling



Safety net applied to Heavy Acoustic Ceilings



Safety Net at School Gym in Saitama

K. Kawaguchi

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<https://jp.trip.com/travel-guide/attraction/toronto/cn-tower-80782/>

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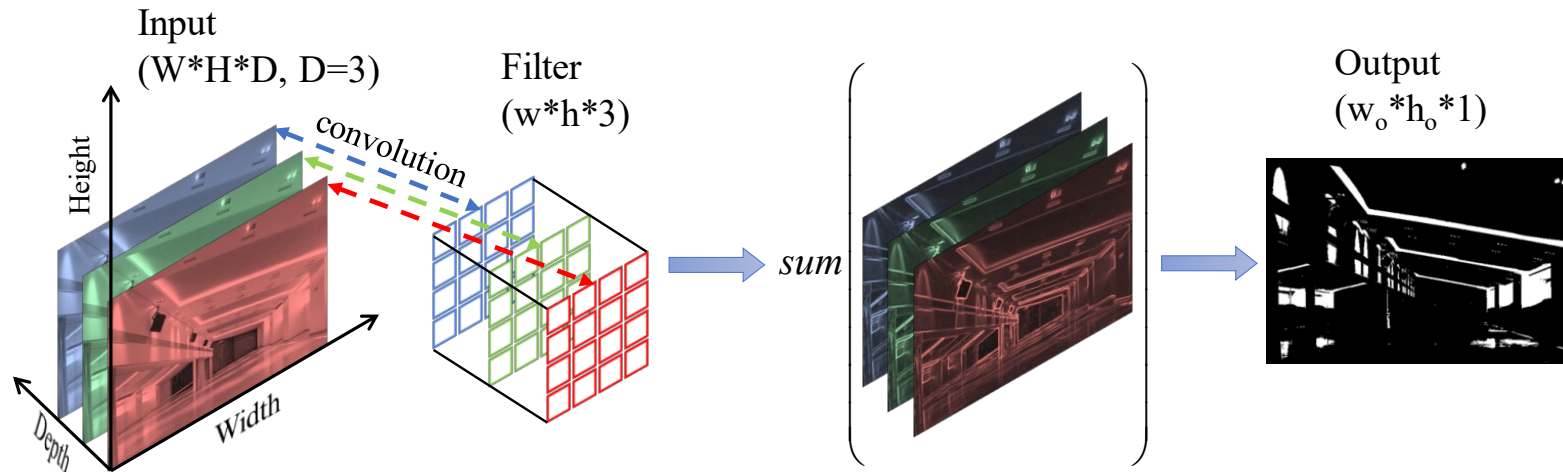


Non-Structural Components

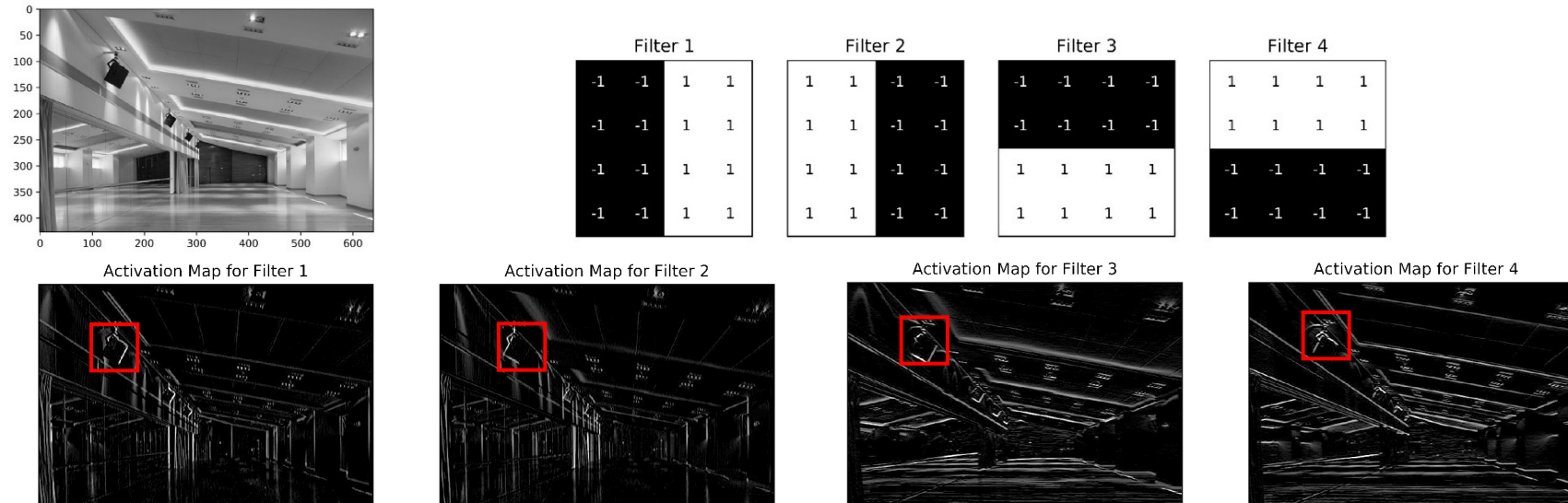
Inspection

For Large Space and Ceilings, Human Visual Inspection is very difficult

Deep Learning and CNN method

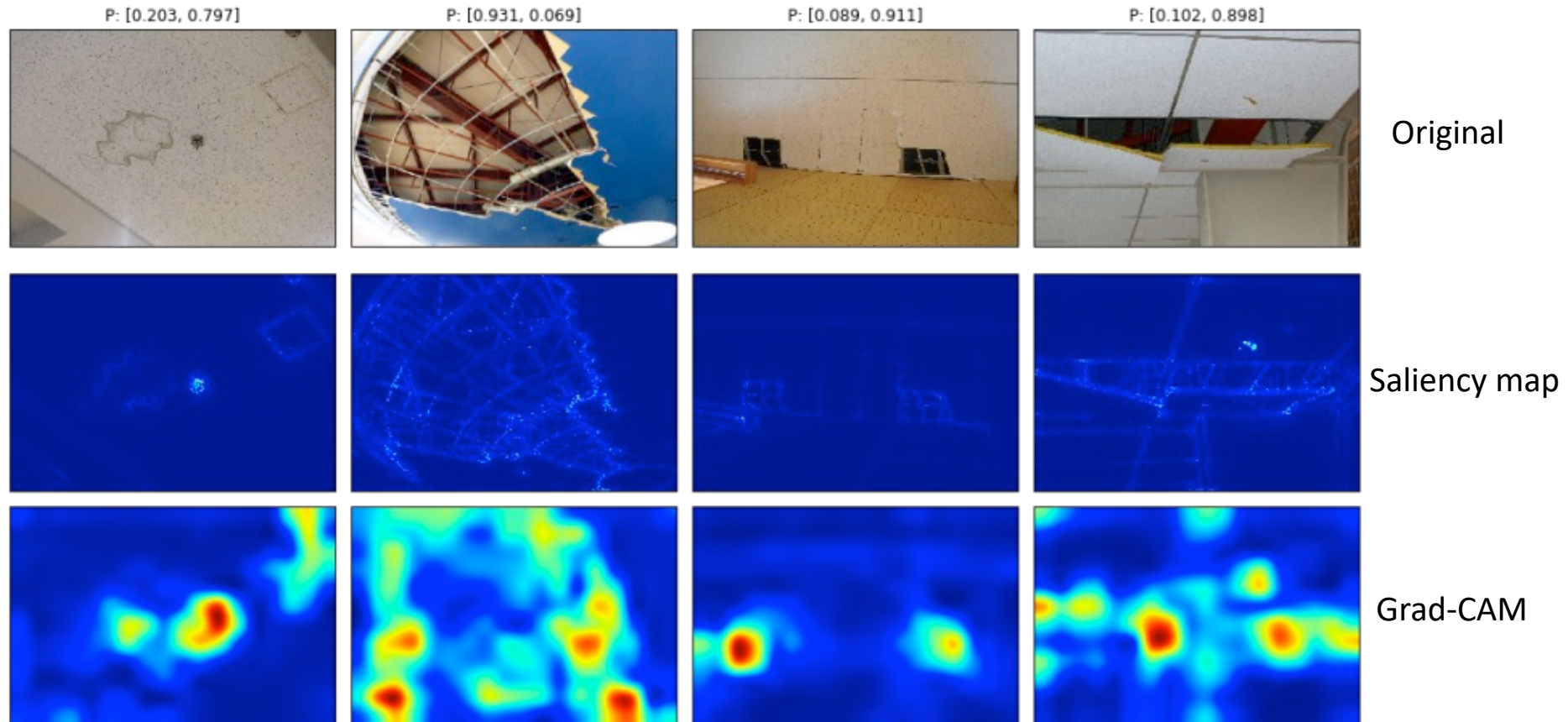


3D filters for Convolution of color images



Edge extraction by filters

Ceiling damage evaluation and its visualization



Result examples of the TF_VGG19 model (2)

撮影者とインタラクティブに損傷個所を同定するスマホアプリの開発

スマートフォンのカメラで撮った写真をそのまま判定！



撮影者とインタラクティブに損傷個所を同定する

April 17, 2024, Bungo-Suido Earthquake, M6.6



Suspended Ceilings in a Public Multi-purpose Hall

Great East Japan Earthquake

March 11, 2011



Music Hall at Fukushima after an earthquake 23:36, Mar.16, 2022



Suspended Ceilings in a Music Hall

K.Kawaguchi

Thank you for your listening!



社会・産業が望む新たな価値： 人類共通の課題・脅威への備え

- ・ 地震、台風、雪害、津波、竜巻や大規模な気候変動
- ・ 様々な抗争による兵器使用、テロ
- ・ 核シェルター、大量破壊兵器
- ・ 伝染病パンデミック
- ・ 大量絶滅を招く天体衝突など、人類の生存を脅かす

巨大災害の脅威



<https://physio-fukuoka.jp/archives/1871>



<https://www.independent.co.uk/news/world/asia/south-korea-troops-mobilised-after-record-snow-2215079.html>



<https://denvercatholic.org/middle-east-crisis/>



<https://www.props.eric-hart.com/safety/n95-day/>



<https://abcnews.go.com/US/asteroid-wiped-dinosaurs-powerful-10-billion-atomic-bombs/story?id=65537028>

最も安全で安心な空間確保の技術が望まれている。

社会・産業が望む新たな価値： 人類共通の課題・脅威への備え

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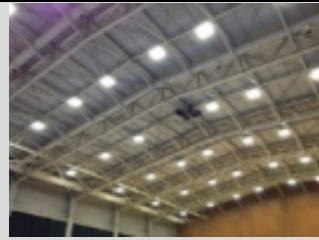
<https://abcnews.go.com/US/asteroid-wiped-dinosaurs-powerful-10-billion-atomic-bombs/story?id=65537028>

最も安全で安心な空間確保の技術が望まれている。

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Ceiling Damage Detecting System by Deep Learning Approach



(1) 0.0758



(2) 0.264



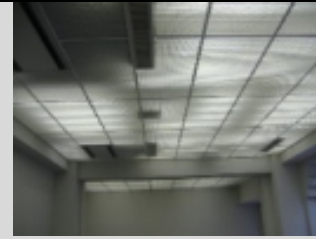
(3) 0.294



(4) 0.108



(5) 0.312



(6) 0.350



(7) 0.246



(8) 0.954



(9) 1.120



(10) 1.353

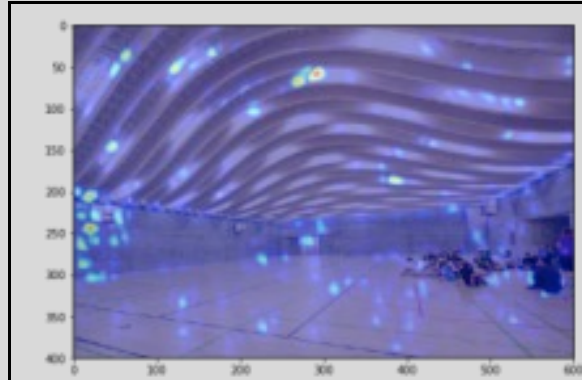


(11) 0.614

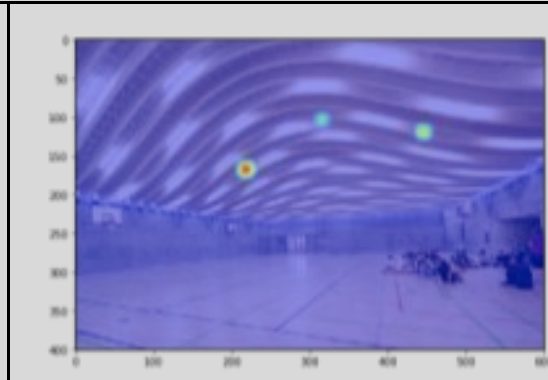


(12) 1.060

Ceiling Damage Detecting System by Deep Learning Approach



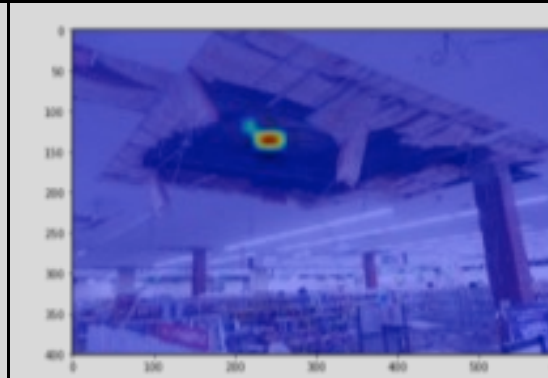
Saliency map to the ceiling image (intact)



grad-CAM to the ceiling image (intact)



Saliency map to the ceiling image (damaged)



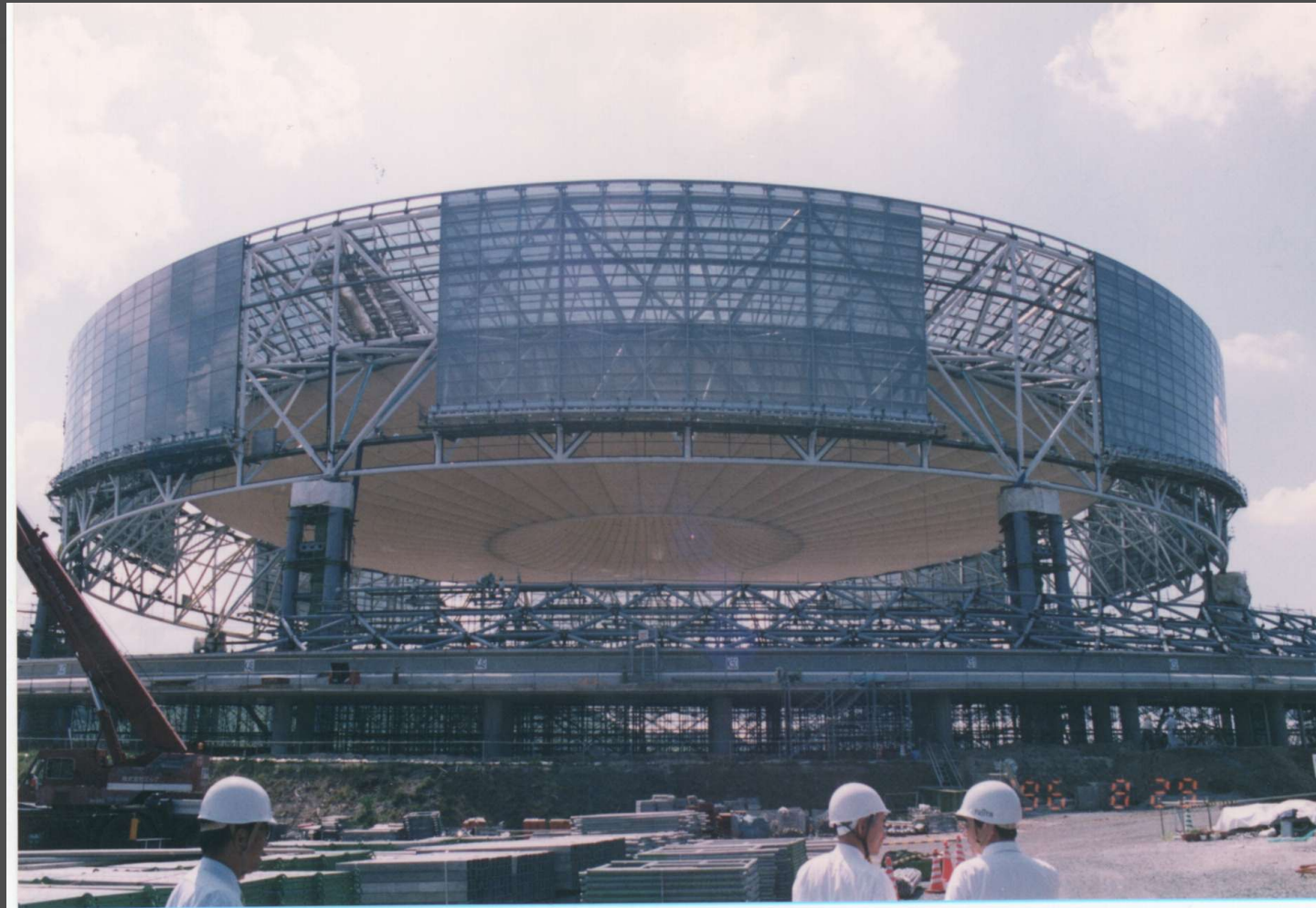
grad-CAM to the ceiling image (damaged)

Membrane Roofs during Strong Wind



Izumo Dome 2004 (<https://mapio.net/images-p/3501554.jpg>)

Kumamoto Dome, 1998



Completed in 1998, 200mx200m Air-inflated Membrane

Kumamoto Dome, 1999, After a Typhoon



**Failure of Air Inflated Membrane
Structure in Heavy Wind and Rain**



K.Kawaguchi

Membrane Warehouses damaged by Typhoon 21 in 2018



Images from Internet

Failure of cladding must be controlled



Images from Internet

Eye of Yellow Sea: 黄海之眼

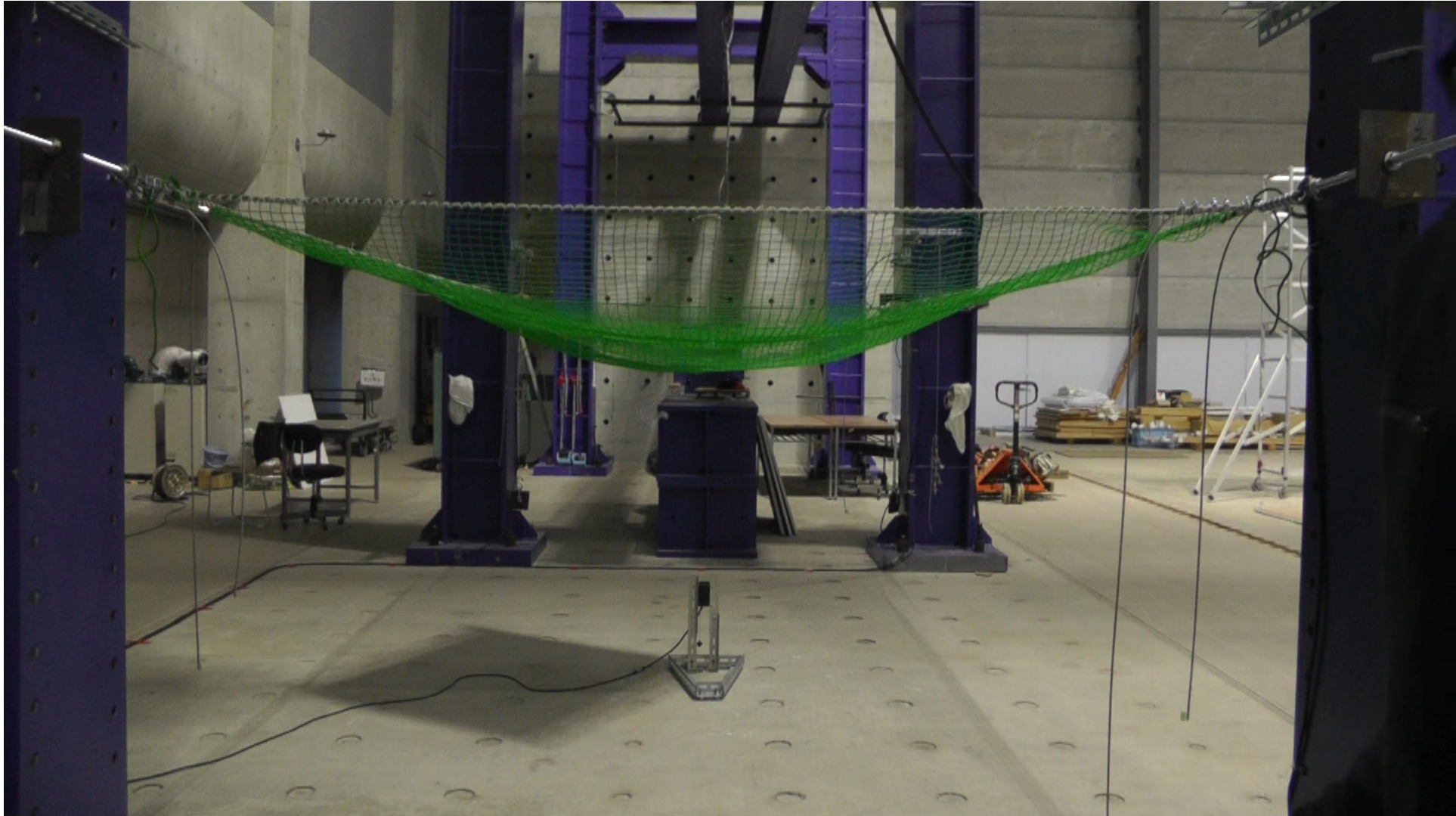


日照市: 中国

Eye of Yellow Sea: 黄海之眼

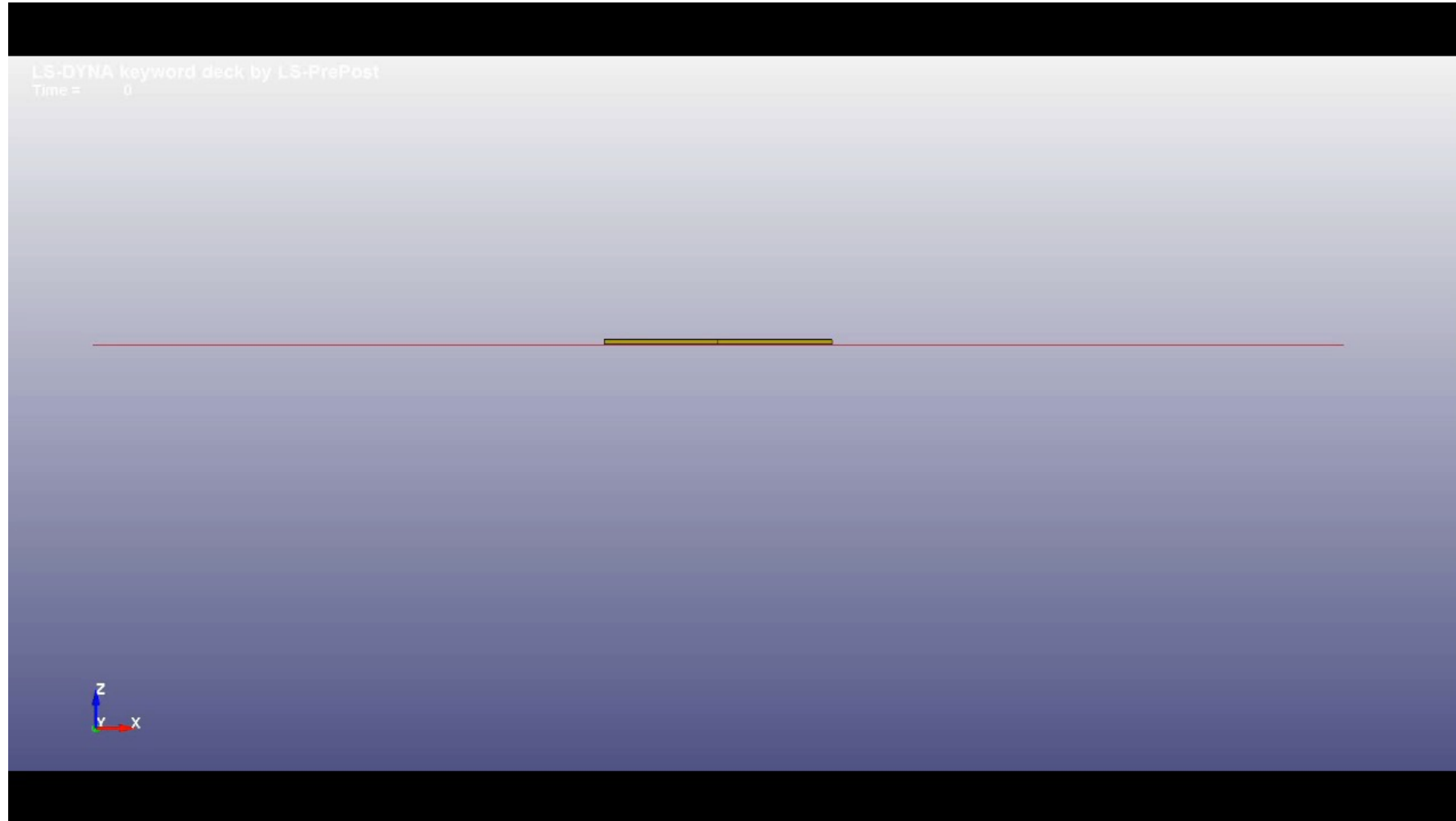


Research of How to design Safety Nets

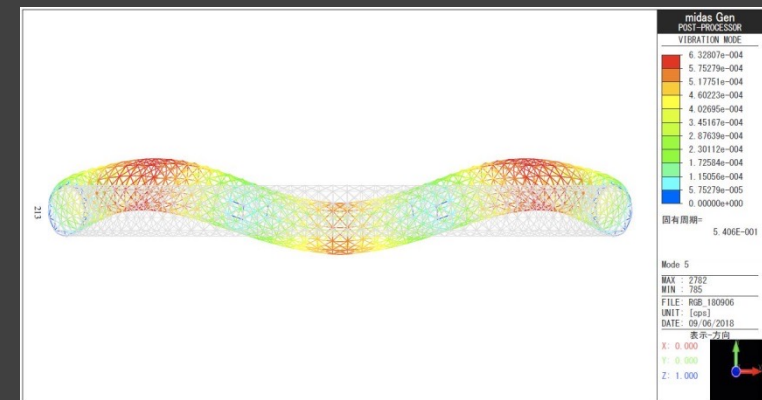
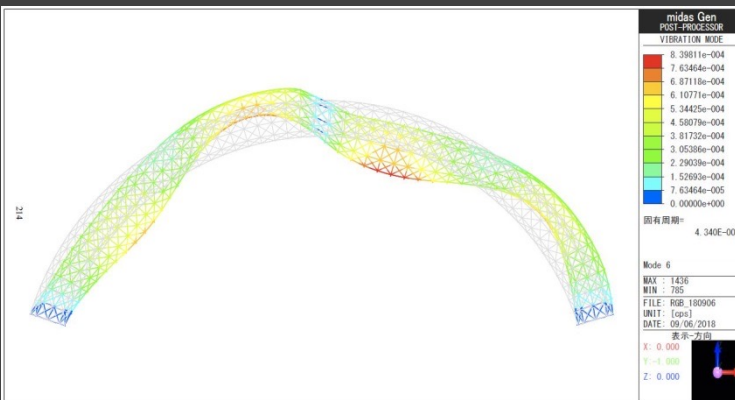
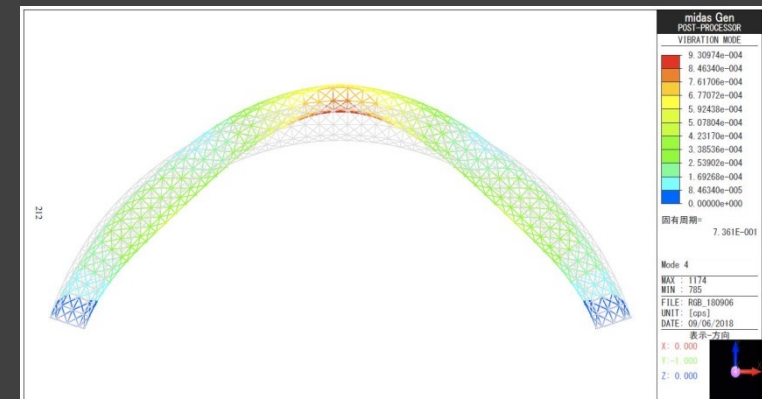
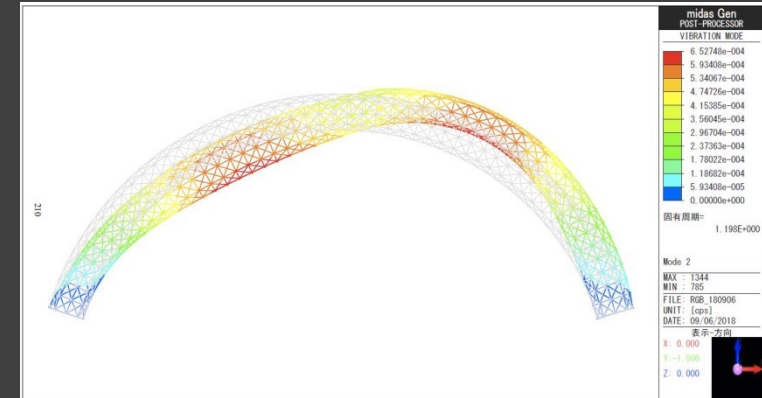
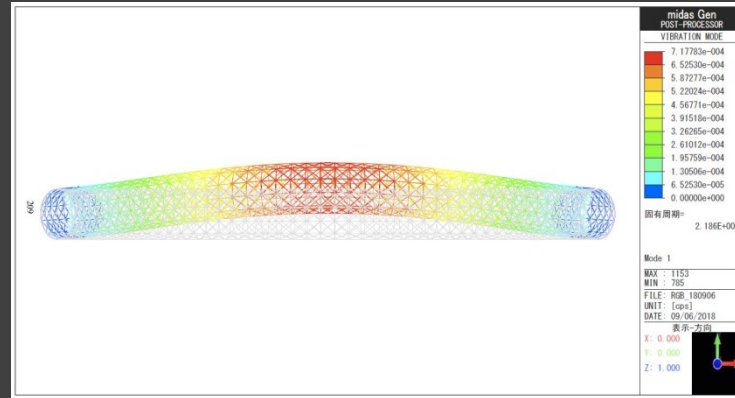


K. Kawaguchi

Research of How to design Safety Nets



Eye of Yellow Sea: 黄海之眼



高所設置の非構造材の被害



1995年1月17日 阪神・淡路大震災による天井落下事例



2011年3月11日 東日本大震災による天井落下被害



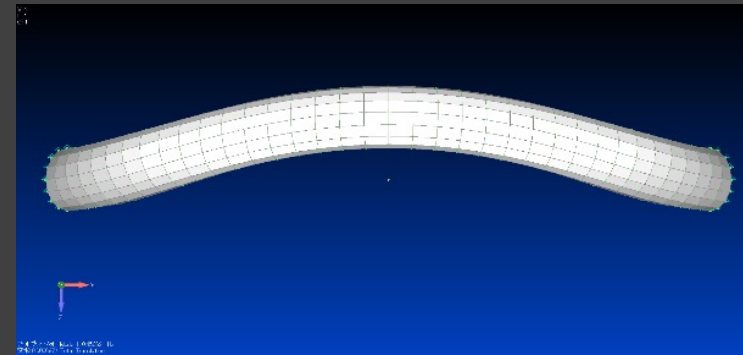
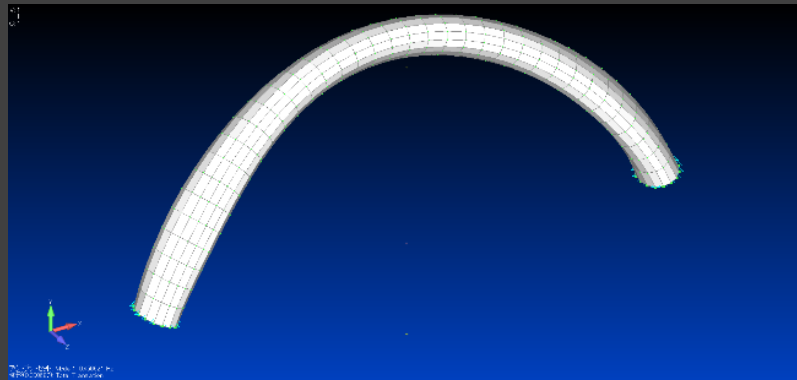
2019_11_06_ロンドンピカデリー劇場上演中の天井落下被害
BBC_News Japan より _109554299_hole



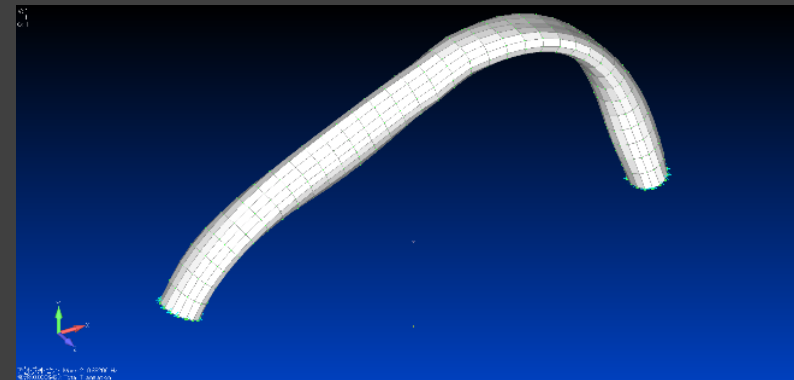
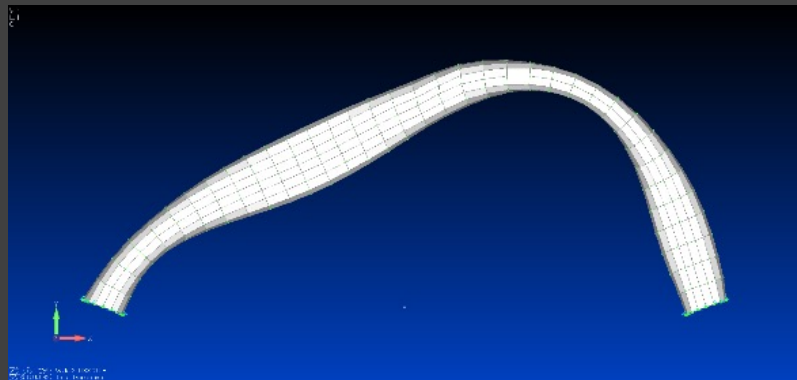
人体耐性指標による
天井の安全性評価



Eye of Yellow Sea: 黄海之眼



(a) 1st mode

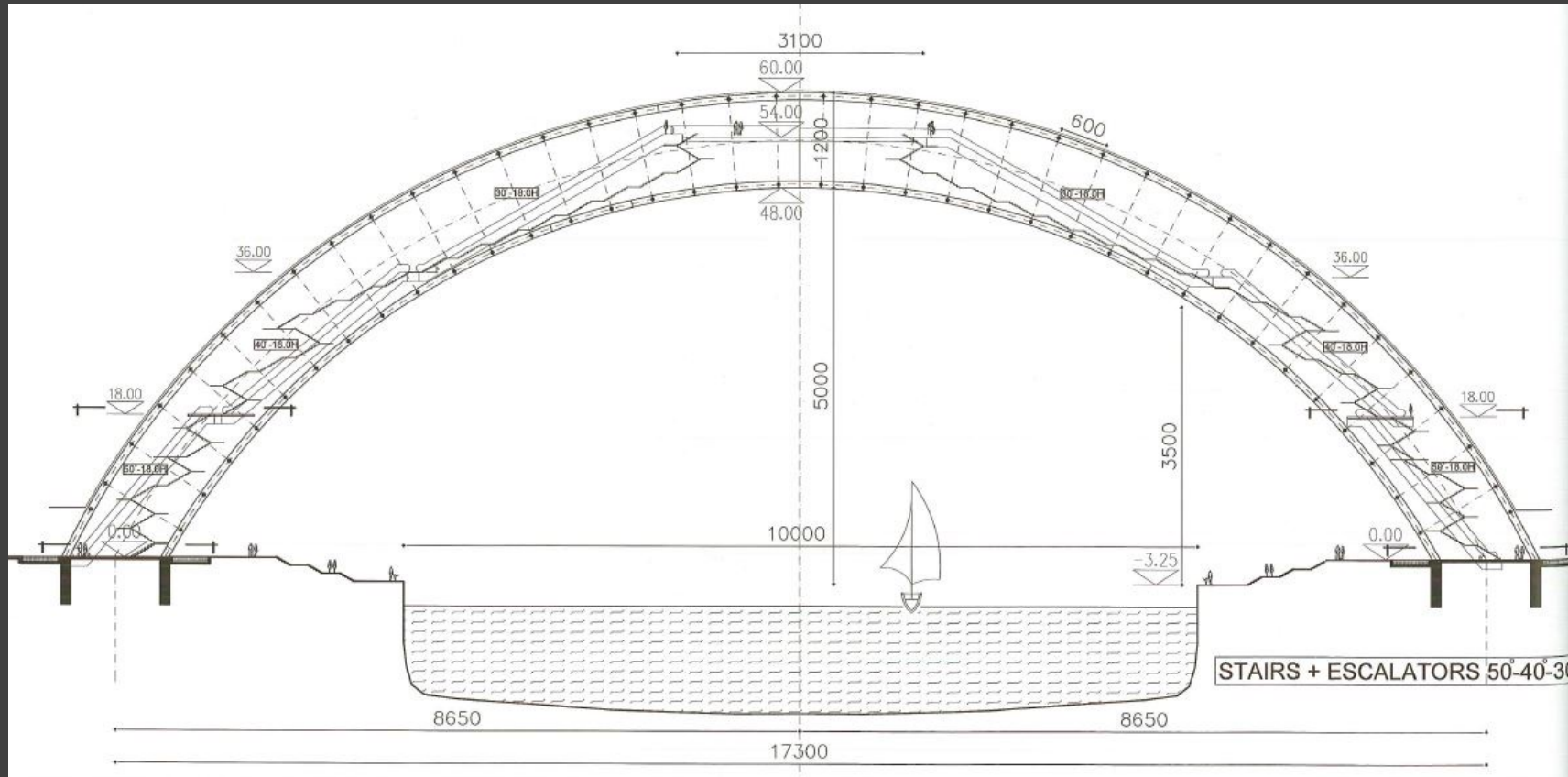


(b) 2nd mode

Eye of Yellow Sea: 黄海之眼

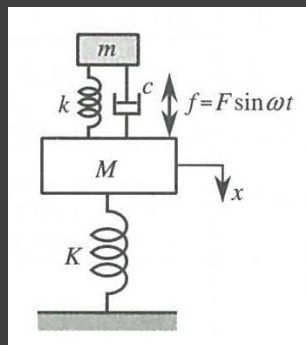
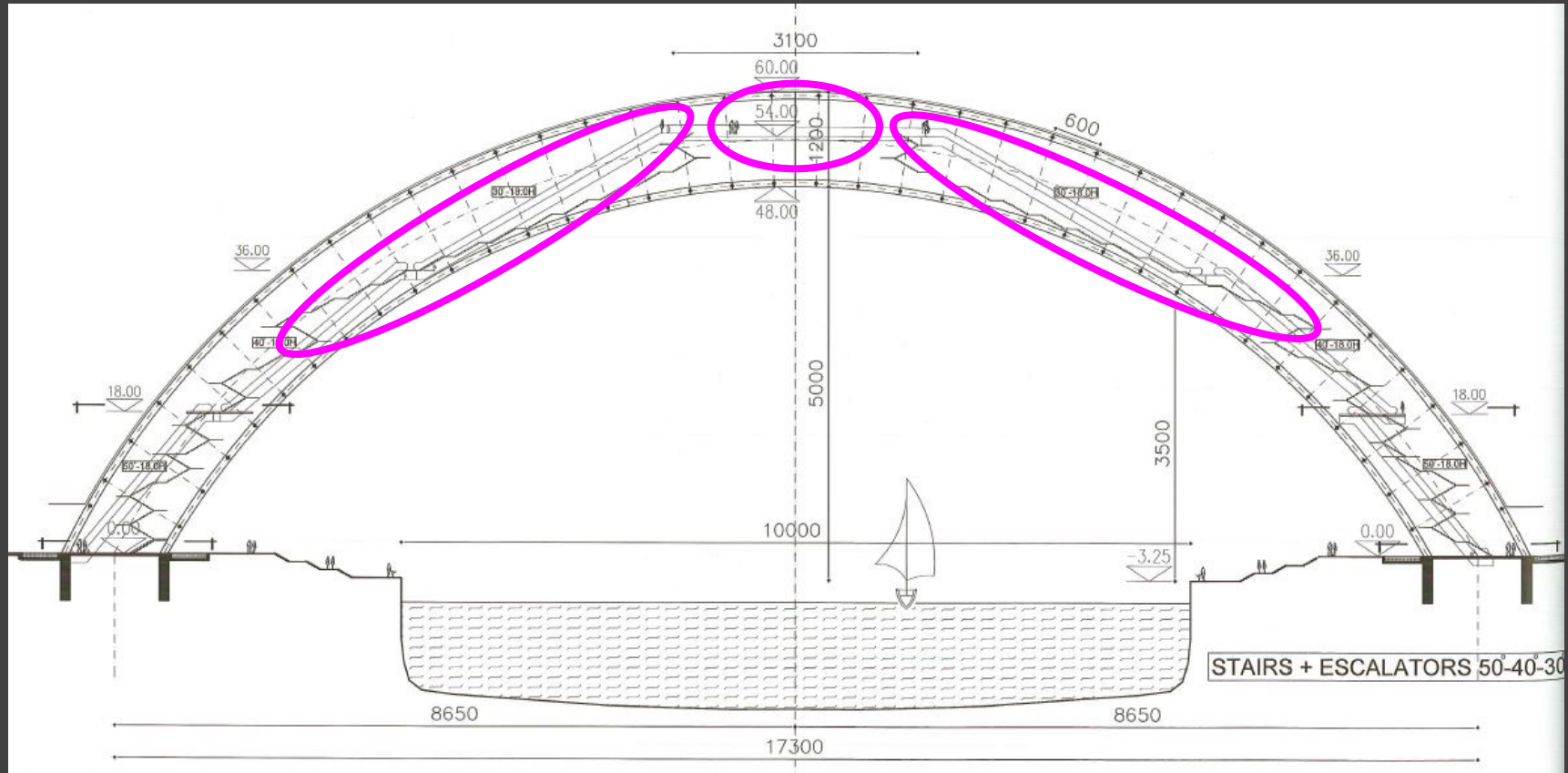


Eye of Yellow Sea: 黄海之眼

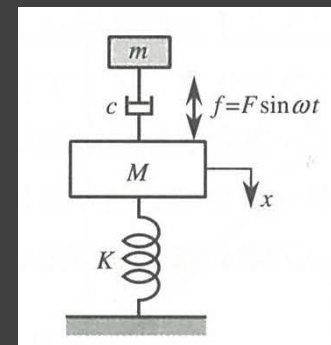


Steel Structure with less damping
→ Additional damping

Eye of Yellow Sea: 黄海之眼

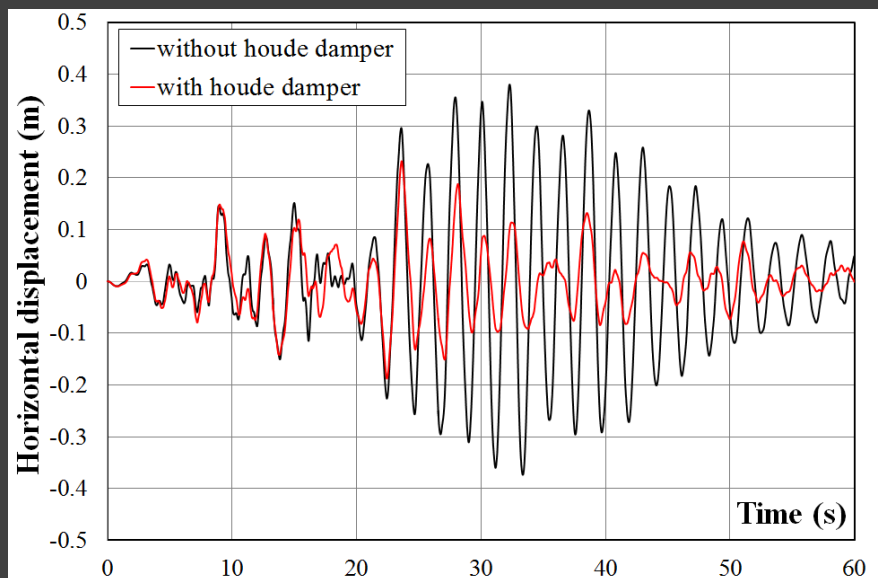


Tuned
Mass
Damper

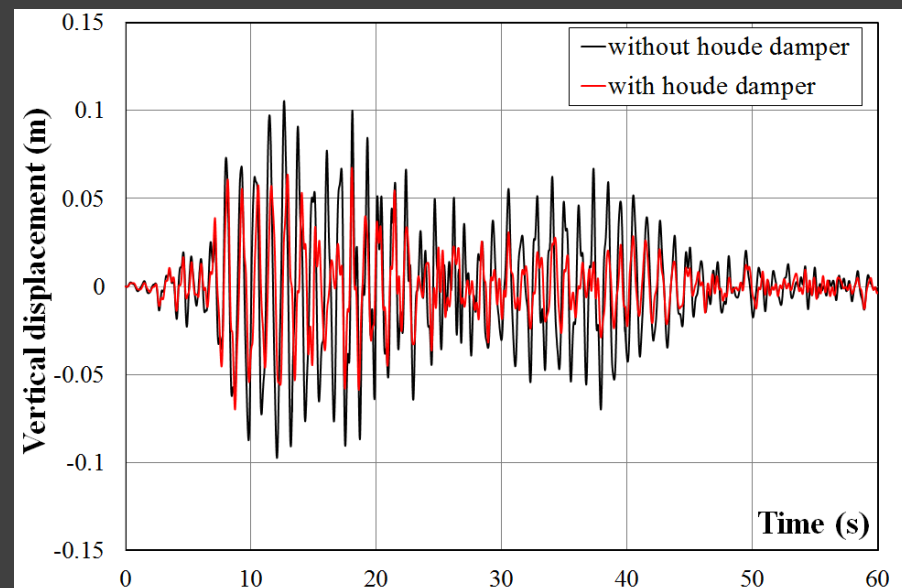


Houver
Damper

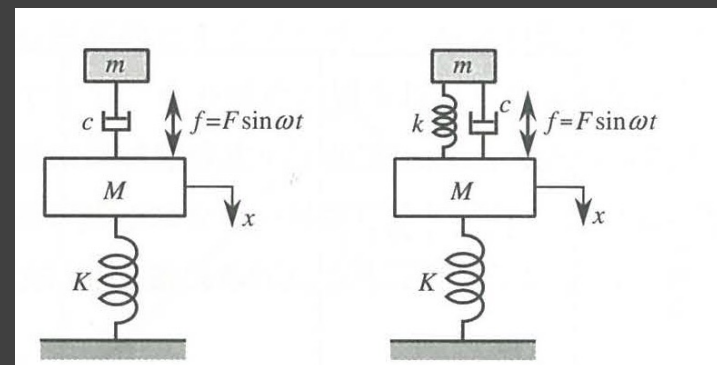
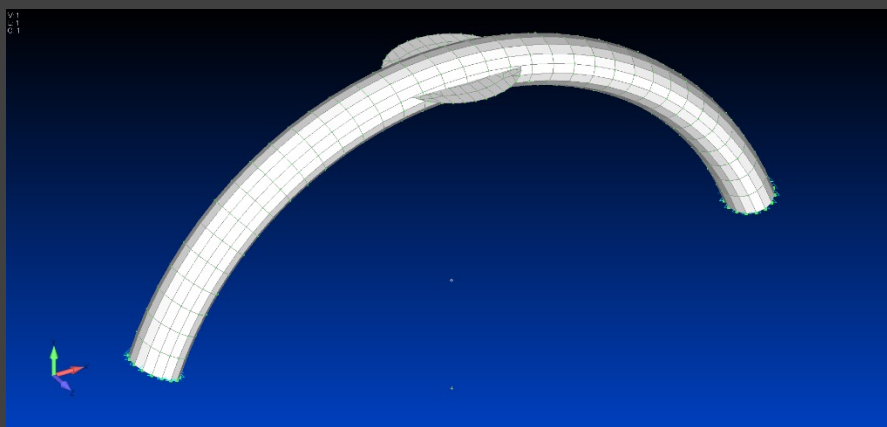
Eye of Yellow Sea: 黄海之眼



Time history response mode1 (yz)



Time history response mode1 (xz)



Long-Span Roof Structures

- Seismic Load (Earthquake)
- Snow Load
- Wind Load
- Remarks

Long-Span Roof Structures

- **Seismic Load (Earthquake)**
 - **Lighter and lighter Ceilings**
- **Snow Load**
 - **Force limiter**
- **Wind Load**
 - **Houwer dumpers**

Long-Span Roof Structures

- Seismic Load (Earthquake)
 - Lighter and lither Ceilings
- Snow Load
 - Force limiter
- Wind Load
 - Houver dumpers

IASS Recommendations

- WG 3 Recommendations for the Design of Hyperbolic or other Similarly Shaped Cooling Towers, Paduart, A. et al., IASS, 1977
- WG4 Recommendations for Guyed Masts, Mogensen, I. et al., IASS, 1981
Recommendations for Safe Systems for Access on Masts and Towers, Grant, M. et al., IASS, 2001
- WG 5 Recommendations for Reinforced Concrete Shells and Folded Plates, Medwadowski, S. J. et al., IASS, 1979
- WG 7 Recommendations for Air-Supported Structures, Tsuboi, Y. et al., IASS, 1985
- WG 8 Analysis, Design and Realization of Space Frames, IASS, 1984, Tsuboi, Y. et al.,
Guide to Buckling Load Evaluation of Metal Reticulated Roof Structures, Kato, S. et al., Draft, September, IASS, 2014
Guide to Earthquake Response Evaluation of Metal Roof Spatial Structures, Takeuchi T., Xue S.-D., Shiro Kato S. et al., IASS, 2019
- WG 19 Structural Design Guidelines for Temporary Spatial Structures, Murota, T. et al., IASS, 2015

Long-Span Roof Structures

- **Seismic Load (Earthquake)**
 - **Lighter and lighter Ceilings**
- **Snow Load**
 - **Force limiter**
- **Wind Load**
 - **Houwer dumpers**

Structural Components

Components

- Structural Components
- Non-Structural Components

Disturbance

- Time Dependent Damage -> Inspection (Difficulty of Human visual inspection)
- Event Dependent Damage -> Severe Natural Disaster (Strong wind, Heavy Snow, Earthquake), Manmade Disaster (War, Terror Attack, Vandalism, Fire...)

For Reliability of Spatial Structures

Structural Safety

- Force Control
- Damage Control

Life Safety

- Fail-Safe

Strong Wind

Components

- Structural Components (1st and 2nd)
- Non-Structural Components

Disturbance

- Time Dependent Damage -> Inspection (Difficulty of Human visual inspection)
- Event Dependent Damage -> Severe Natural Disaster (Strong wind, Heavy Snow, Earthquake), Manmade Disaster (War, Terror Attack, Vandalism, Fire...)

Earthquakes

Components

- Structural Components
- Non-Structural Components

Disturbance

- Time Dependent Damage -> Inspection (Difficulty of Human visual inspection)
- Event Dependent Damage -> Severe Natural Disaster (Strong wind, Heavy Snow, Earthquake), Manmade Disaster (War, Terror Attack, Vandalism, Fire...)

Non-Structural Components

Components

- Structural Components
- Non-Structural Components

Disturbance

- Time Dependent Damage -> Inspection (Difficulty of Human visual inspection)
- Event Dependent Damage -> Severe Natural Disaster (Strong wind, Heavy Snow, Earthquake), Manmade Disaster (War, Terror Attack, Vandalism, Fire...)

Catastrophic collapse of Spatial Structures by Heavy Snow, 2004-2006



Swimming Pool in Moscow,
Feb.14, 2004



Ice skate link
in Germany Jan 2nd 2006



Exhibition Hall
in Poland, Jan.28th,2006



IASS Recommendations

- Recommendations for the Design of Hyperbolic or other Similarly Shaped Cooling Towers, 1977 (WG 3)
- Recommendations for Guyed Masts, 1981 (WG4)
Recommendations for Safe Systems for Access on Masts and Towers, 2001 (WG4)
- Recommendations for Reinforced Concrete Shells and Folded Plates, 1979 (WG 5)
- Recommendations for Air-Supported Structures, 1985 (WG 7)
- Analysis, Design and Realization of Space Frames, 1984 (WG 8)
Guide to Buckling Load Evaluation of Metal Reticulated Roof Structures, 2014 (WG 8)
Guide to Earthquake Response Evaluation of Metal Roof Spatial Structures, Damage Control of Structural Components 2019 (WG 8)
- Structural Design Guidelines for Temporary Spatial Structures, 2015 (WG 19)