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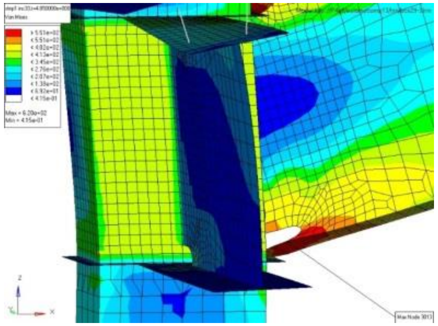
Damage to Steel Buildings after 2011 Tohoku-Oki Earthquake in Japan

December 5, 2016

Lehigh University



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Risk Engineering and System Analytic Center

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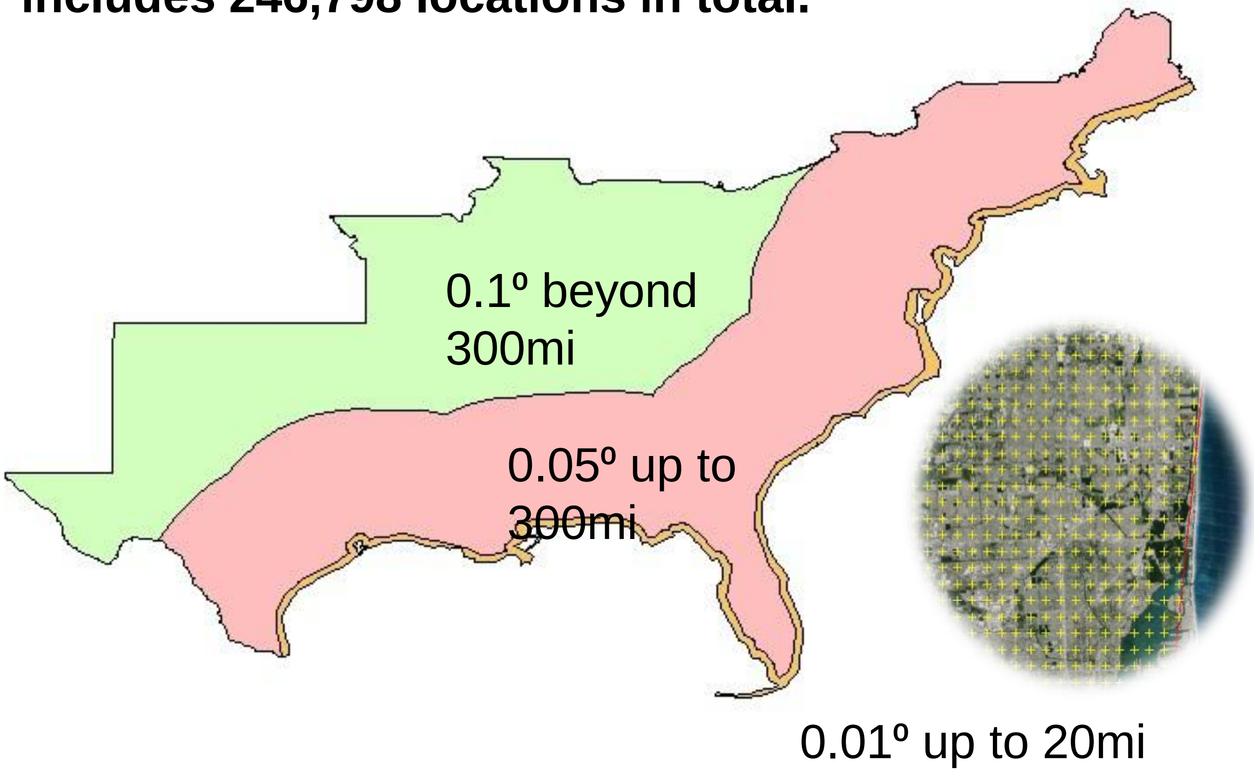
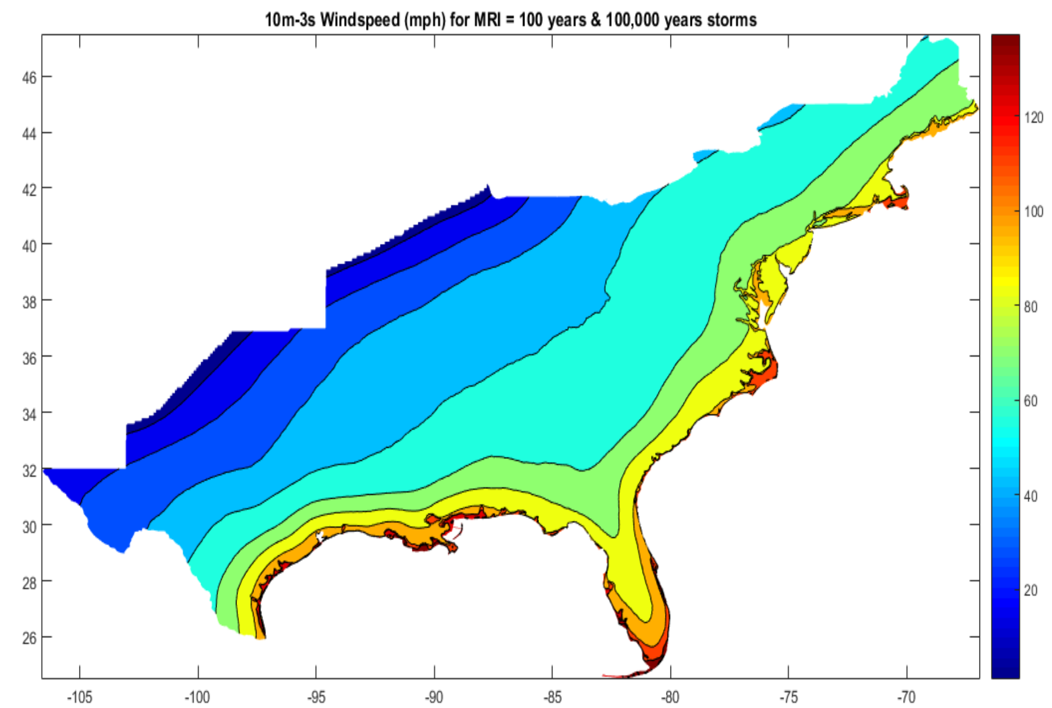
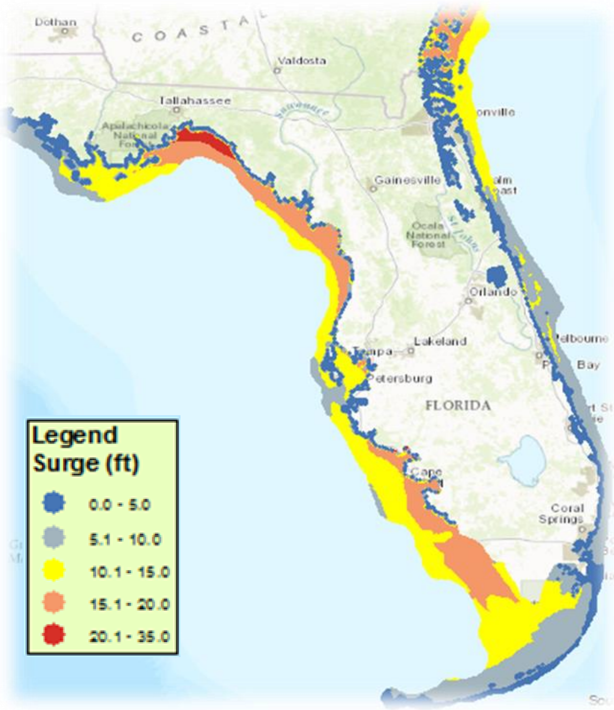
The wind database covers the 30 Eastern US states, and includes 246,798 locations in total.

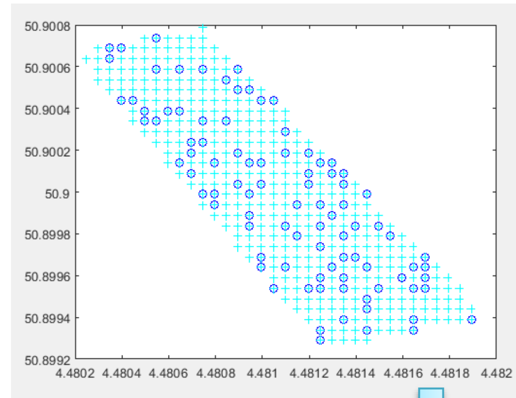


Hurricane wind speed map and storm surge modeling

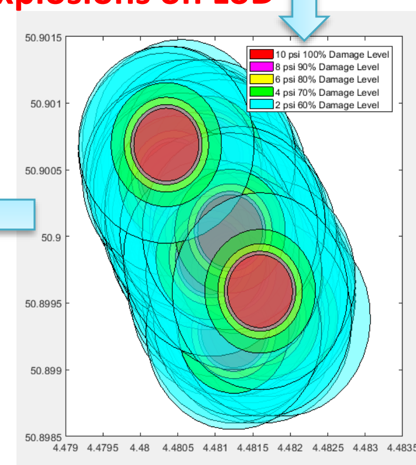




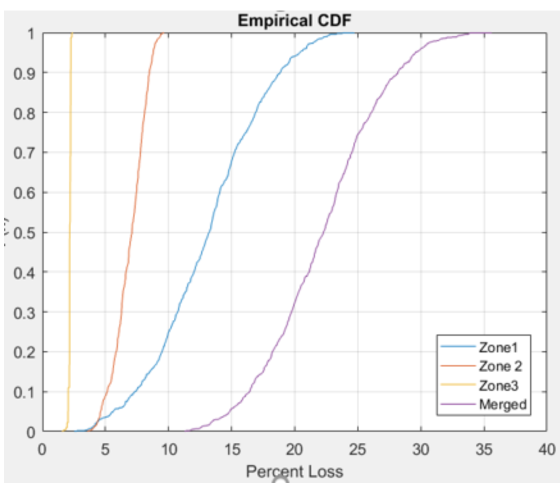
Terrorism Model: Protection Zones



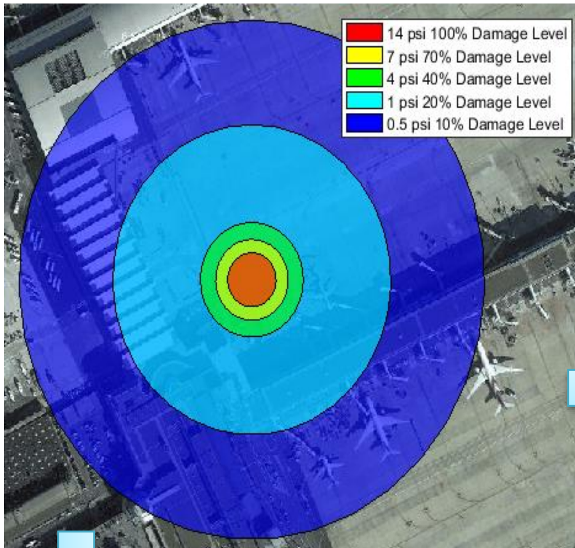
Simulate many explosions on LoD



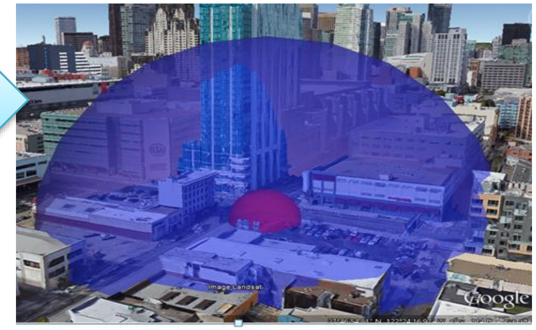
Generate CDF curves for loss in each Protection zones



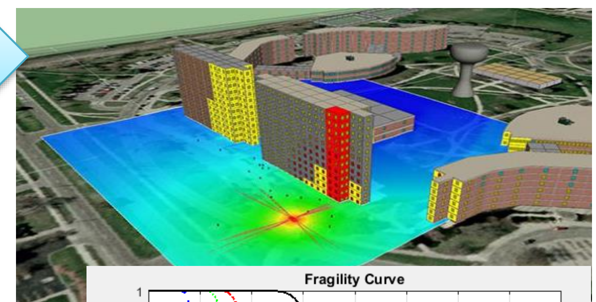
Extending the Model

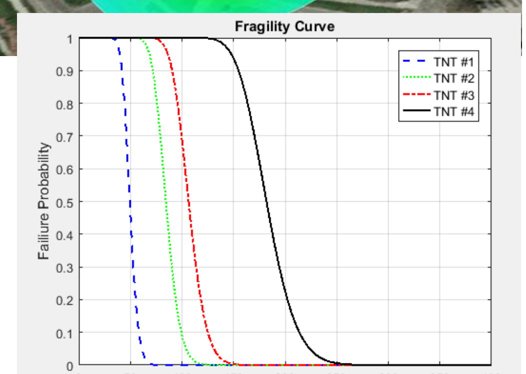


3D-Model

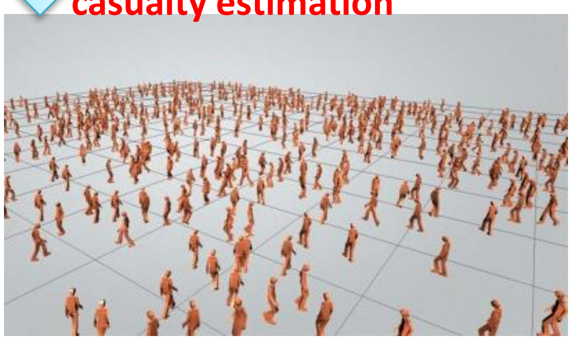


Blast effects on Glazing Damage





Agent Based Model for casualty estimation



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Practice of Steel Structure in Japan

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Part 1:
Introduction:
Practice of Steel Structure in Japan

Tohoku-Oki 2011 Great East Japan Earthquake & Tsunami

New lessons: Tsunami, Tsunami fires, Fukushima power plant

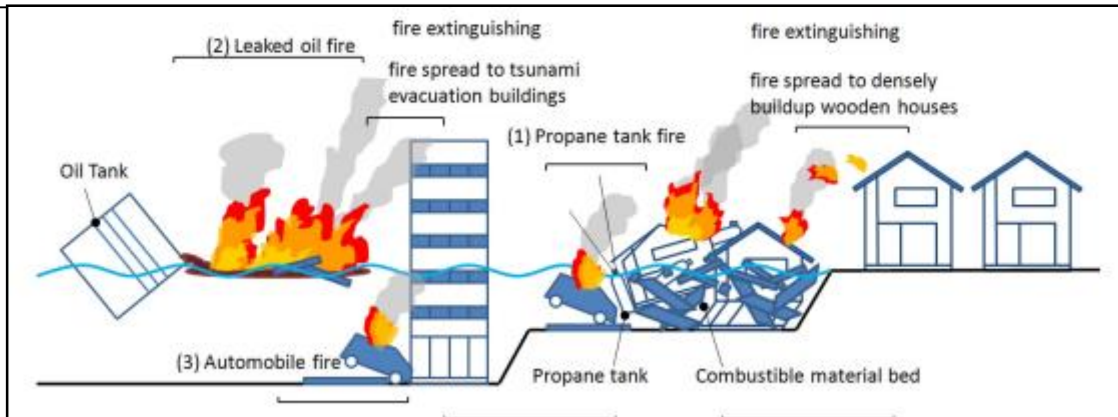
313 Fires recorded

Mechanism of tsunami fires after the Great East Japan Earthquake 2011 – Kobe Uiversity

Mechanism of tsunami fires after the Earthquake 2011

Tsunami after the Earthquake produced a huge impact → oil tanks(ports) + industrial complex + gas cylinders at homes+ automobiles,... were damaged → caused hazardous materials (gas +gasoline in oil tanks+ gas cylinders and fuel tanks) to leak.

sparks from metals which collided each other by tsunami → ignited leaked combustible gases and gasoline to become fires



Historical buildings in different countries

Colosseum (Coliseum)

Tōdai-ji (東大寺)

Arch of Caracalla at Volubilis

Different

Depend on → Environment & available material & …

Conventional Steel Building Structure in Japan

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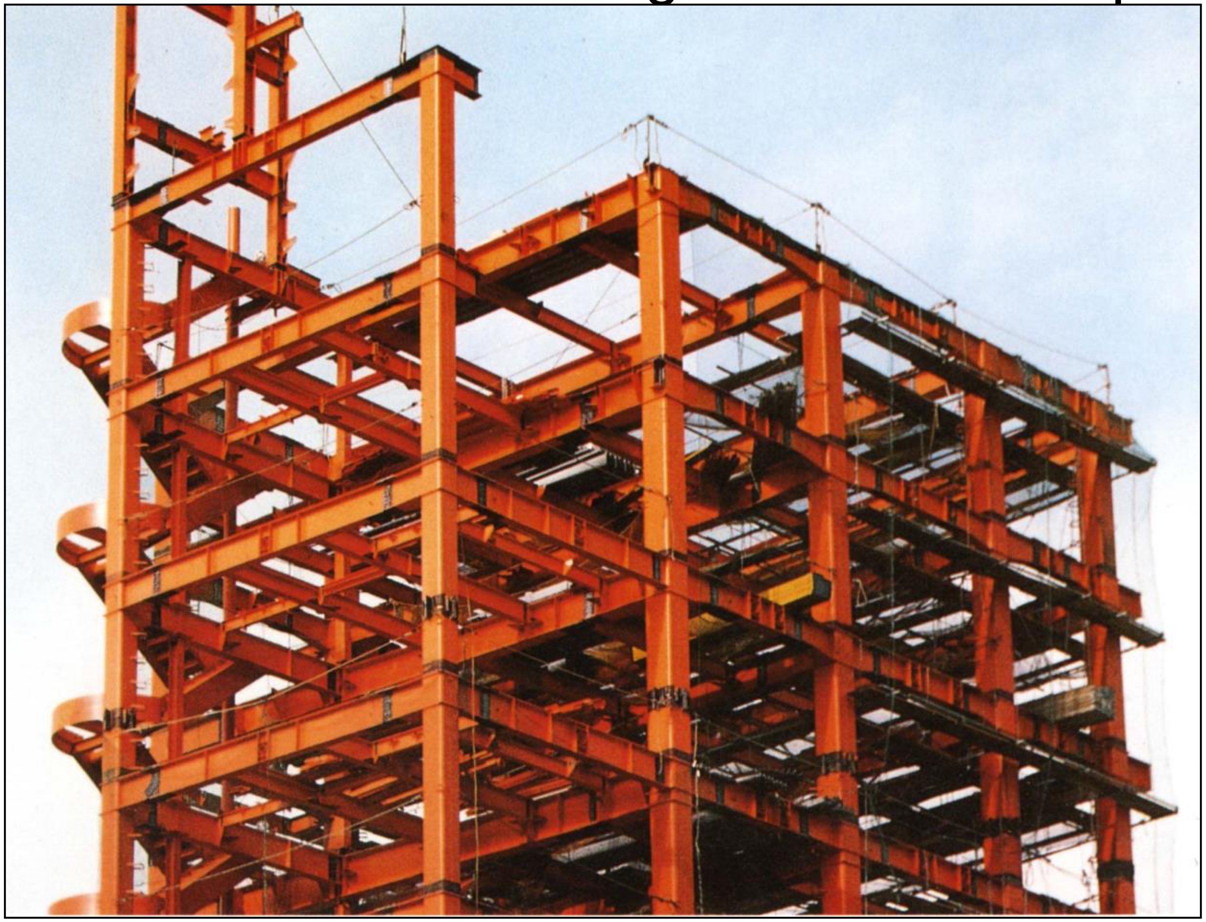
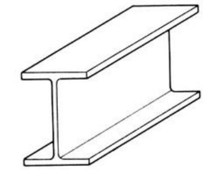
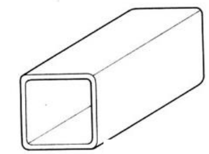


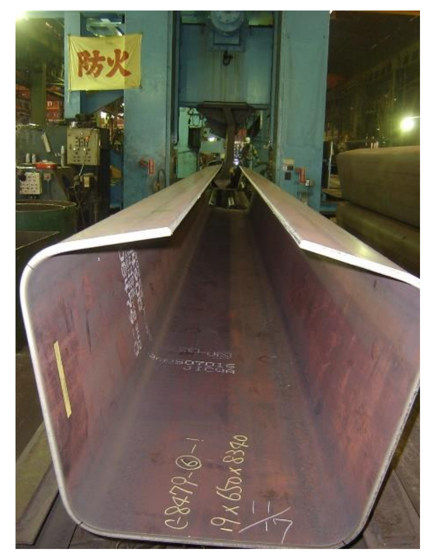


Beam: H-section (wide-flange,WF)



Column: Box section

- **Steel structures have maintained 35% to 40% share of the total constructed floor area since 1985**
- **Majority of steel buildings use full moment-resisting frames (MRFs) with cold-formed, square-HSS columns**

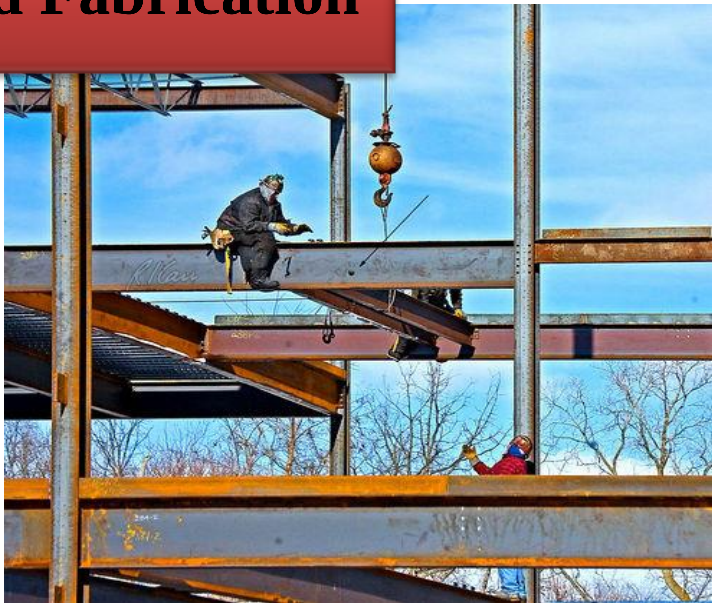


Cold-formed box columns

Differences in Design and Fabrication

US:

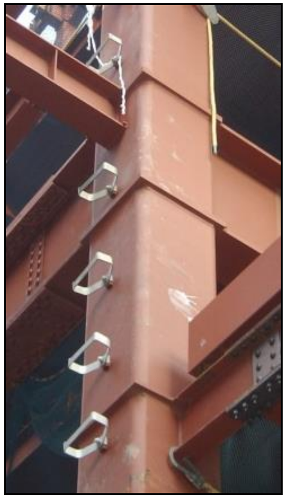
Wide Flange Column sections



Deep Beam for SRLF perimeter frame

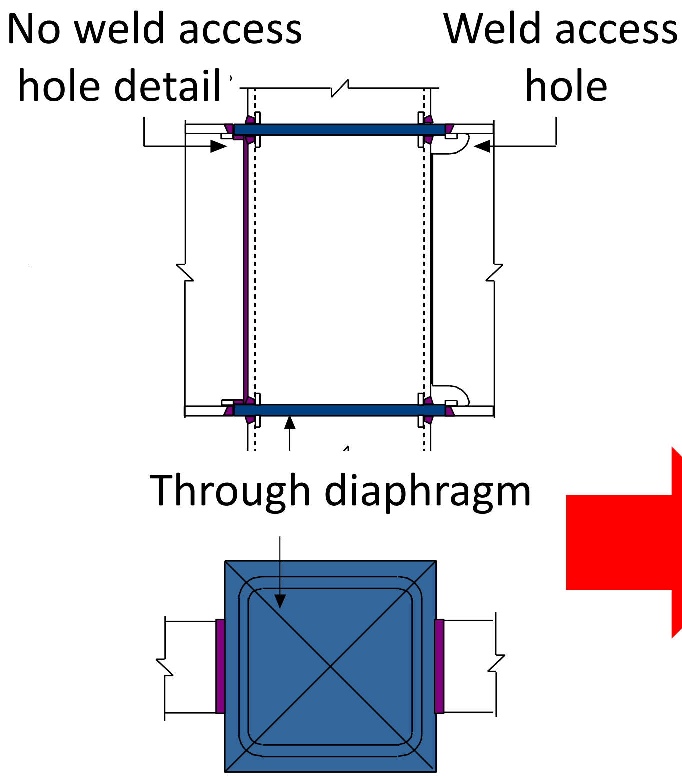
Japan:

Box Column Sections

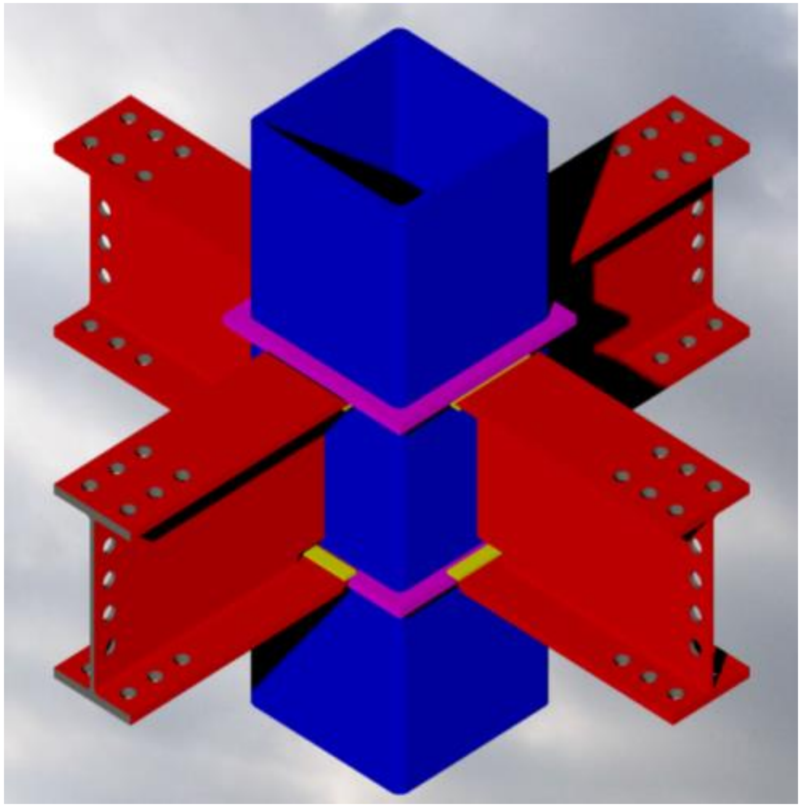


All the frame contribute in SLRF

Dominant practice



RHS column (cold formed) with through-diaphragm

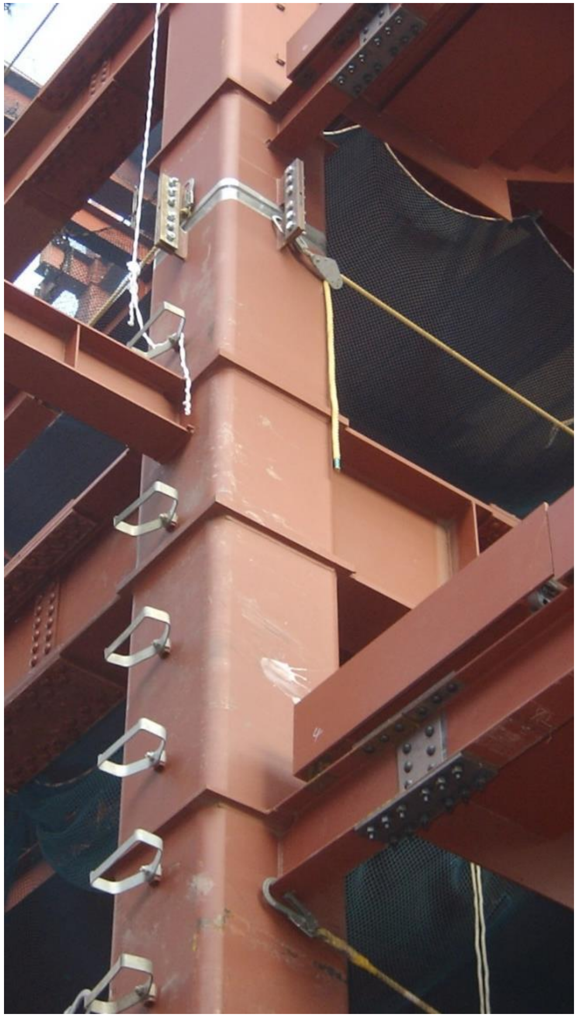


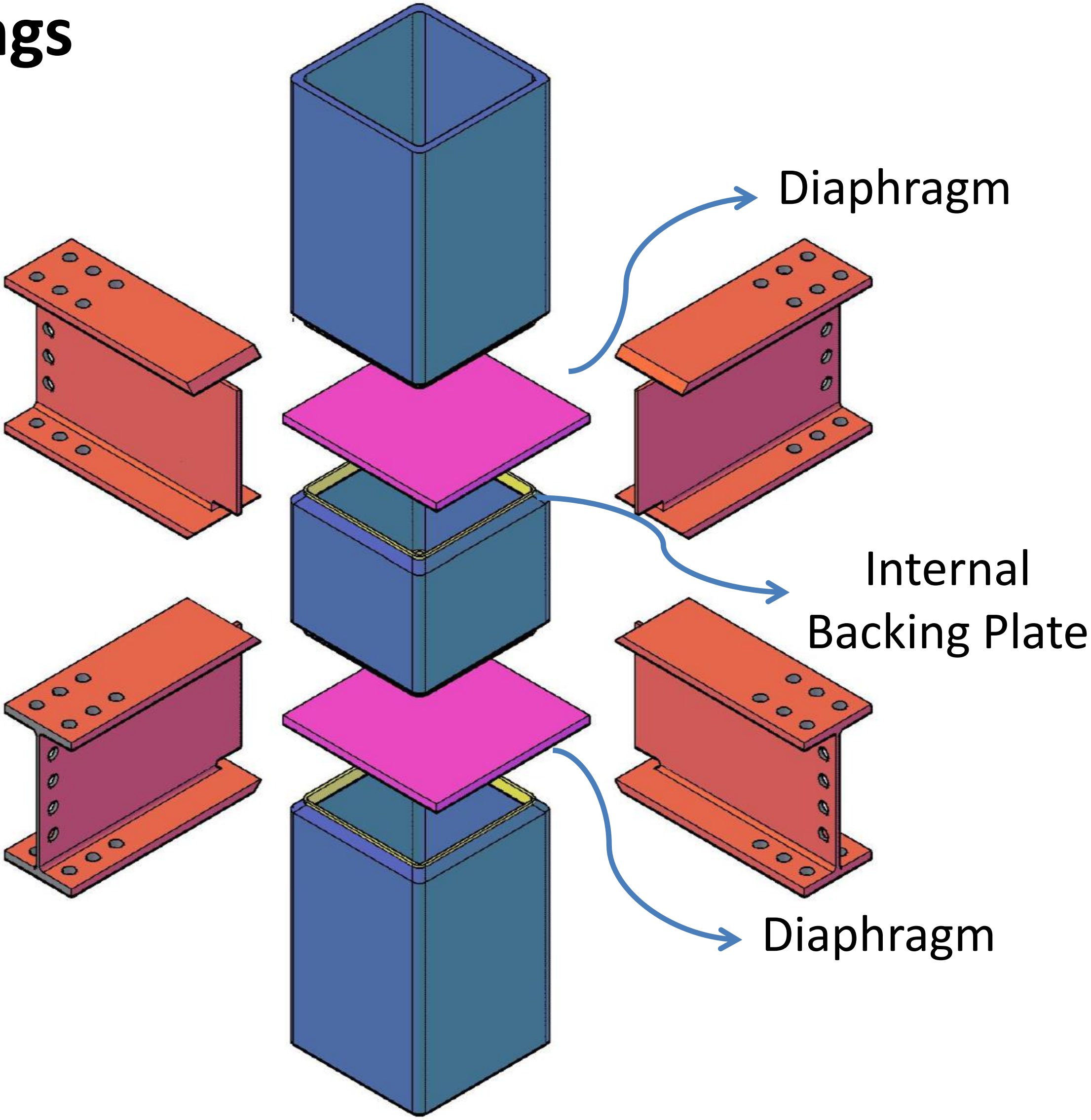
Welded Flange Welded Web (WFWW)

Unlike U.S. construction,

- typical Japanese construction uses beam stubs that are welded to the column in the shop. The middle portion of the beam is bolted to the beam stubs in the field.
- The HSS columns are diced into small segments to insert stiffener plates that act as continuity plates at the location of the beam flanges.

Typical beam-to-column connections in Japan mid-rise buildings





Diaphragm stiffeners are connected to the column by complete-joint penetration groove welds

Beam stubs that are welded to the column in the shop.

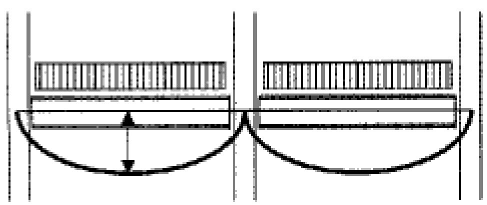
Middle portion of the beam is bolted to the beam stubs in the field

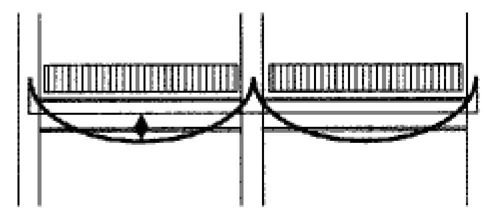
Why Box Shape Column prevails in Japan?

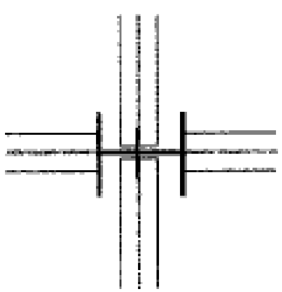
old steel buildings built after the early **1960s** consist of hot-rolled wide-flange steel beams and columns. It was in the early **1980s** that Japanese steel construction moved toward a newer building system consisting of cold-formed steel tube columns and wide-flange steel beams.

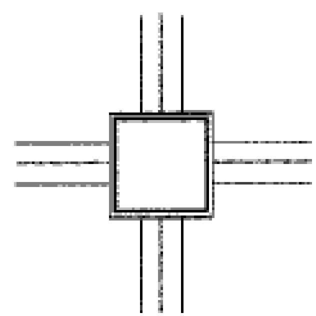
Shear Connection

Rigid connection → **Smaller Bending Moment**
Reduce the beam size









In H-Column → **2 Rigid connection**

In Box Column → ***4 Rigid* connection**

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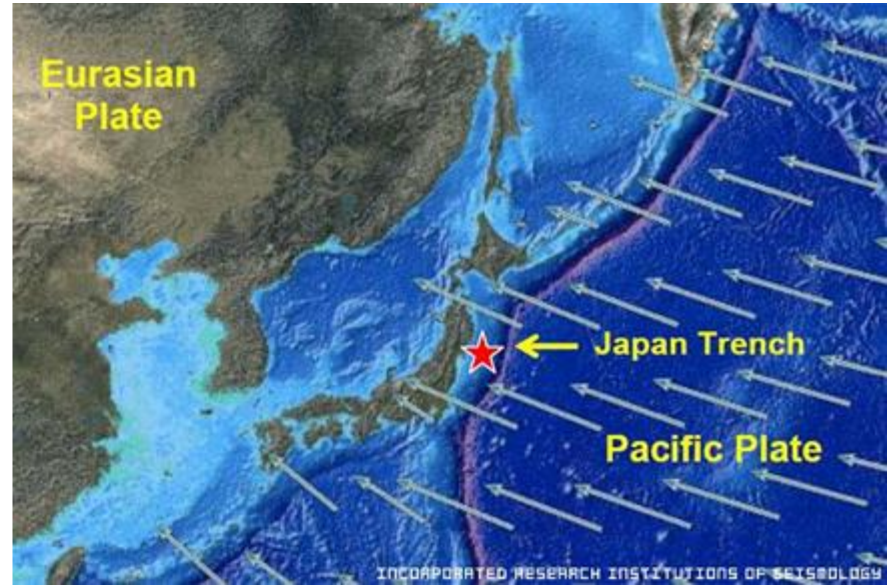
Part 2:
Damage to Steel Buildings after 1995 Kobe Earthquake

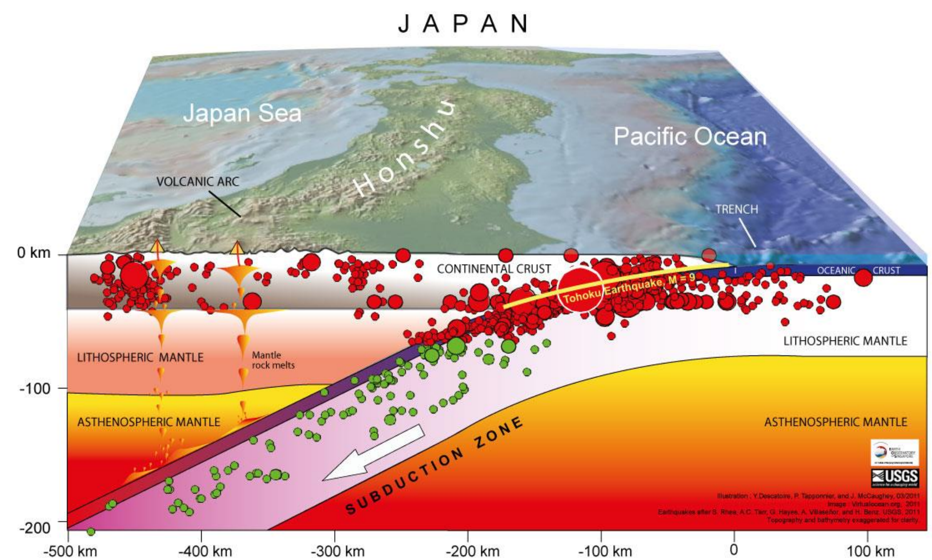
Year	Earthquake	Development of seismic design / Damage
1923	Great Kanto (M7.8)	
1924		Seismic coefficient=0.1 (S.F.=2)
1950		Seismic coefficient=0.2 (S.F.=1)
1968	Tokachi oki (M7.9)	(Shear failure of RC stub column)
1971		(RC :revision of the hoop pitch)
1978	Miyagi-ken oki, M7.2	Damages to brace connections
1981		**Major upgrades of the seismic provision** -Ultimate strength retaining connection design -2ndary design for safety of the life
1995	Hyogoken-Nambu (Kobe),M7.3	Damages to welded beam-to-column connections
1996		Revision of JASS6 Standard
2011	Great East Japan (Tohoku-Oki)	

Tohoku-Oki (2011)

Great Kanto (1923)

Kobe earthquake(1995)

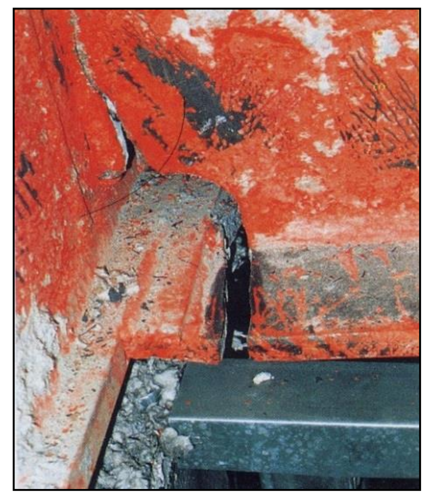




Northridge Earthquake - Kobe earthquake

Northridge Earthquake
US , Jan. 1994
Brittle Fracture of Connections

Kobe Earthquake
Japan , Jan. 1995
Damages to Connections



a number of steel moment frame buildings were found to have experienced fracture at connections. In most of cases fractures happened at bottom flange

similarity in damages → **But Different Solutions**

Although
Differences in industry

Japan

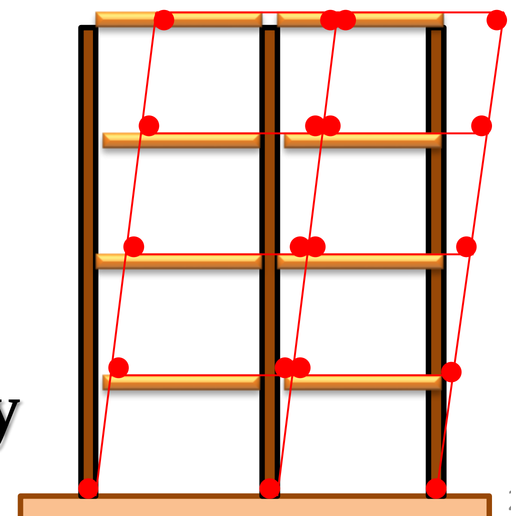
US

A decade after the damages → **Similar efforts:**

US 1994 → 2016

Japan 1995 → 2016

Seismic codes Improvement → **To obtain** → **Ductility**



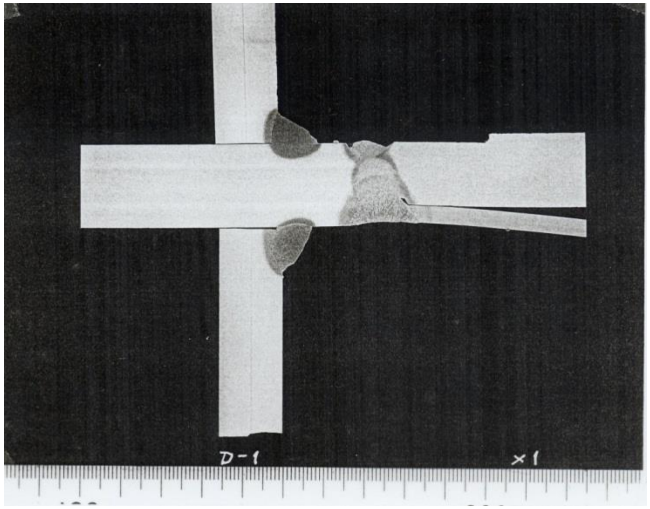
Classification of damages

- Three types of damages

  1. Damages to older steel structures

  2. Damages to newer steel structures resulted from inadequate fabrication

  3. Newly exposed types of damages to newer steel structures



Damage to older structures (Type 1)

3 story building

H shaped section column

Local buckling of the column flange

Shear distortion of the joint panel

1) Lack of the frame strength
2) Large width to thickness ratio of member section.
3) Lack of the reinforcment of joint panel.

Damage Type 2

Damage resulted from **inadequate fabrication** to newer steel structures (Case1)

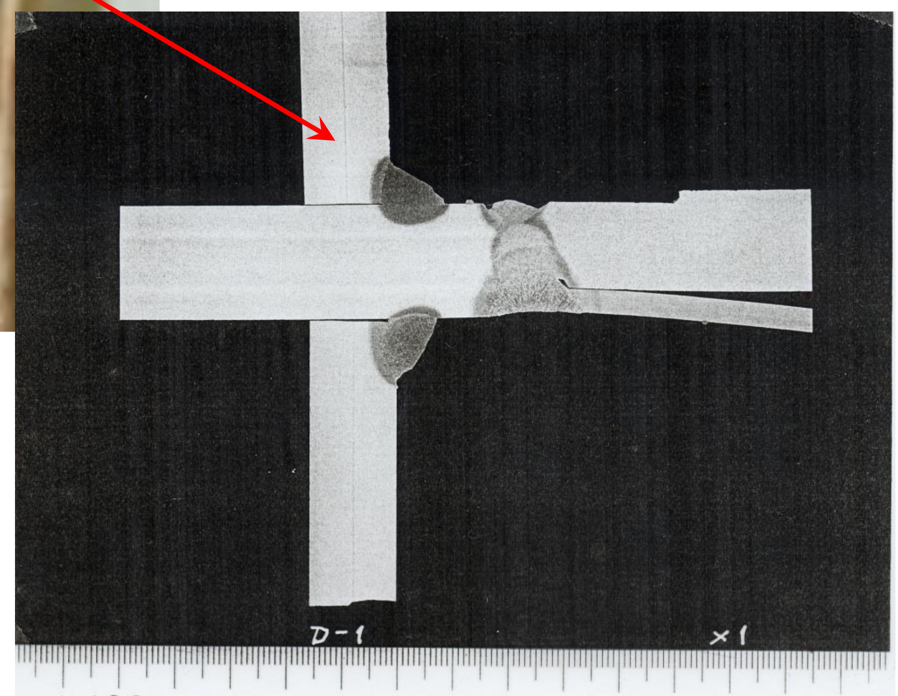
5 story building, Moment frame, Box-column section

Fracture of welds at beam-to-column connection

Inadequate fillet welding

Damage Type 2

Damage resulted from inadequate fabrication to newer steel structures (Case 2)



Improper usage of fillet welding

Fillet welding at only outside of the column

Damage Type 3 (Newly exposed types of damages)

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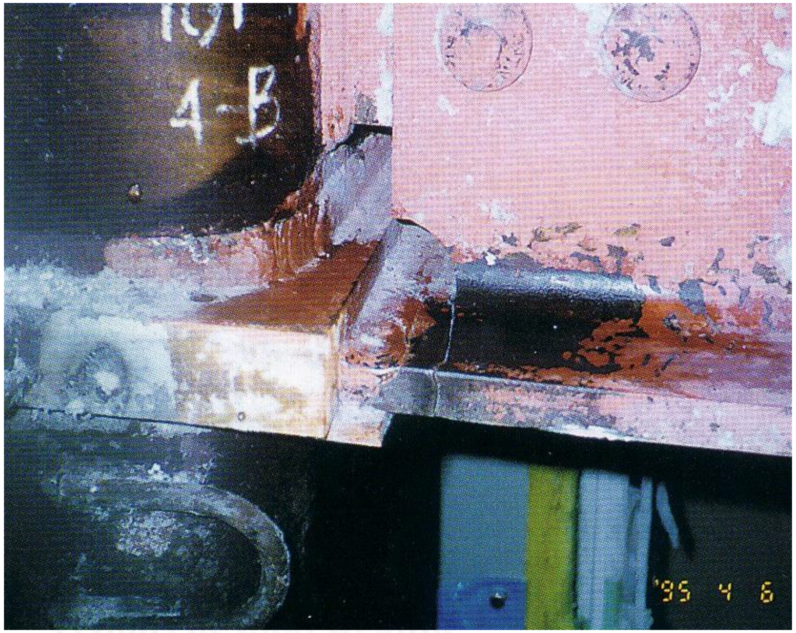
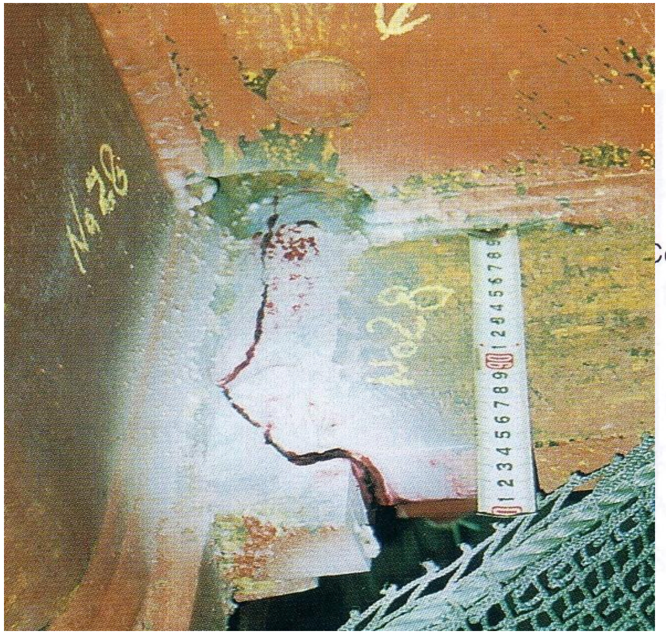
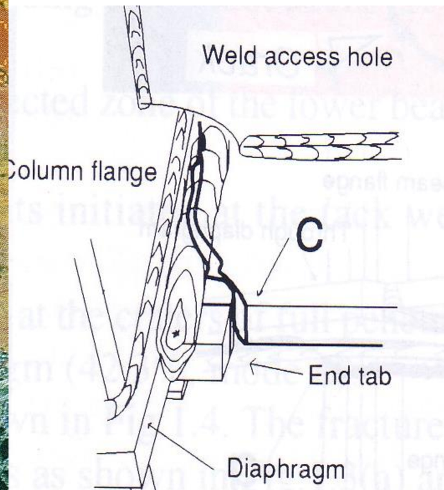
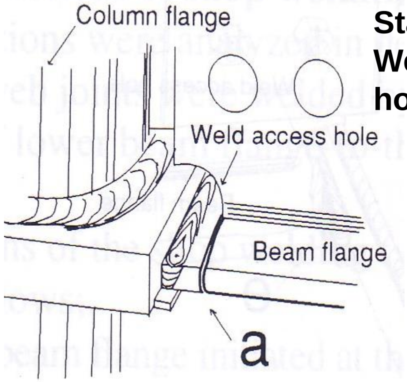


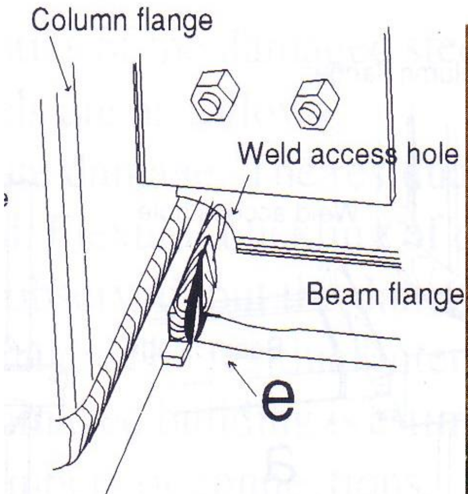


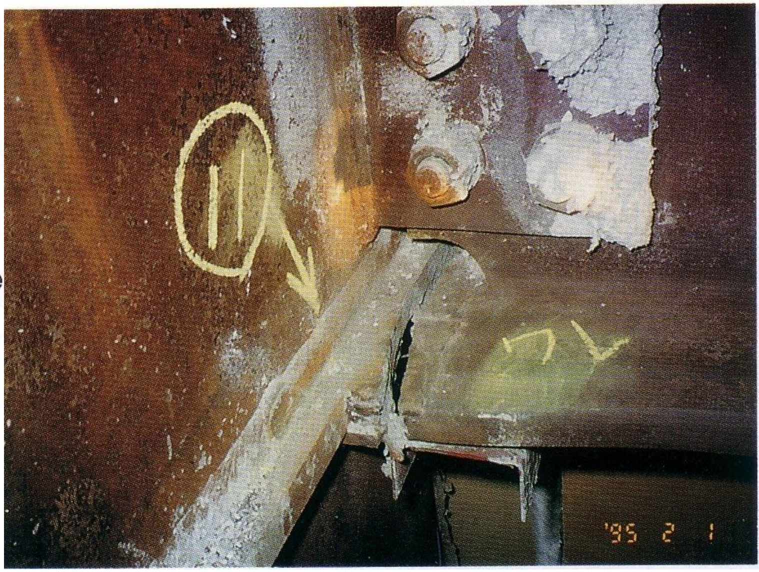


Start from End tab (run-off tub)



Start from Weld access hole (scallop)





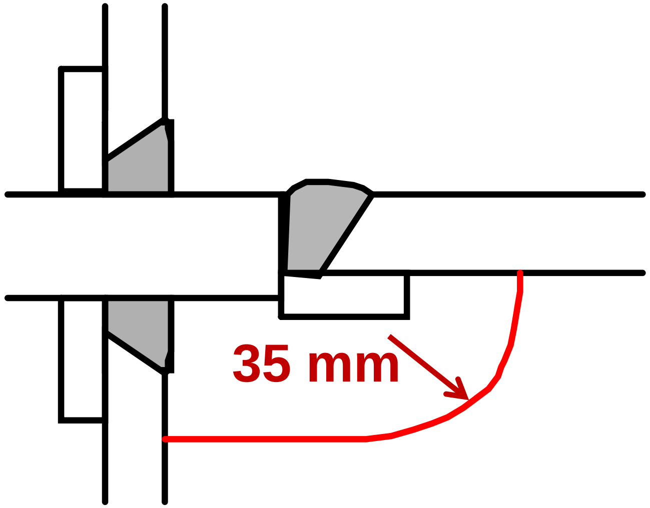
Strat from Improper welding crater

Brittle fractures around beam-column welding joint

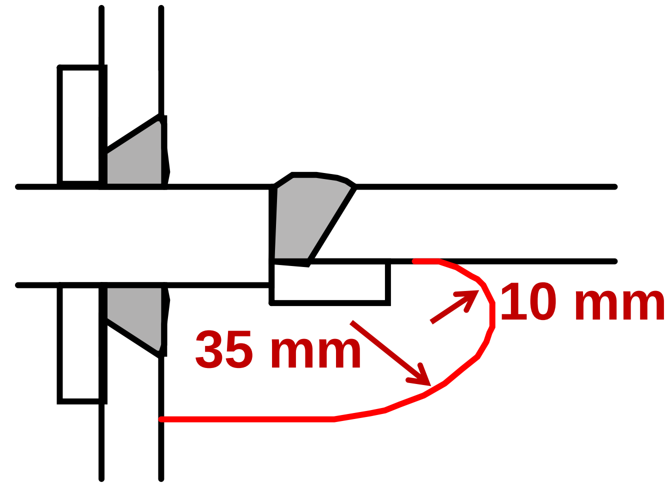
(The pre-qualified welded joints is much more susceptible to damage than was previously expected)

Part 3:
Post-Kobe Earthquake researches

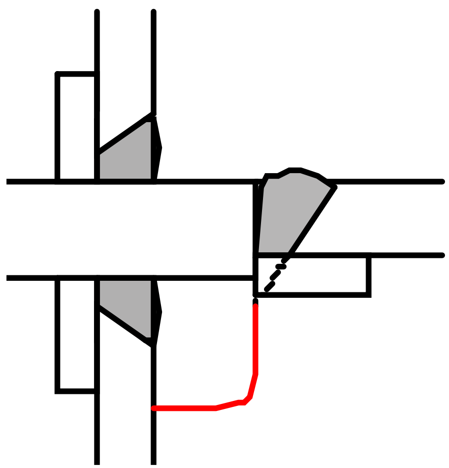
Weld access hole requirements



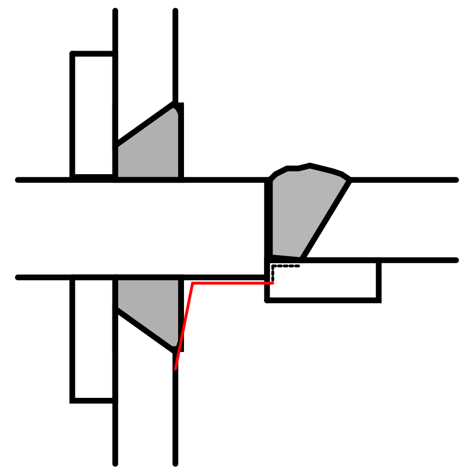
1) Conventional type (35R)



2) Improved type I (35R+10R)



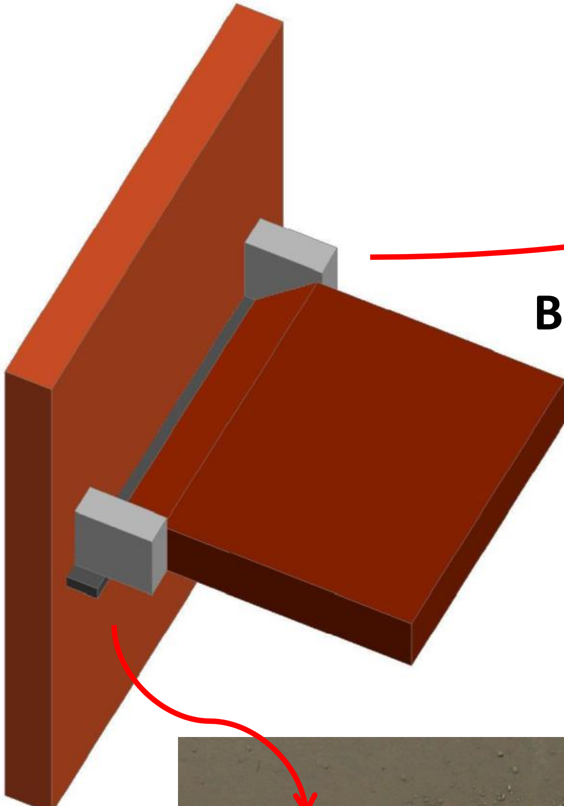
3) Improved type II

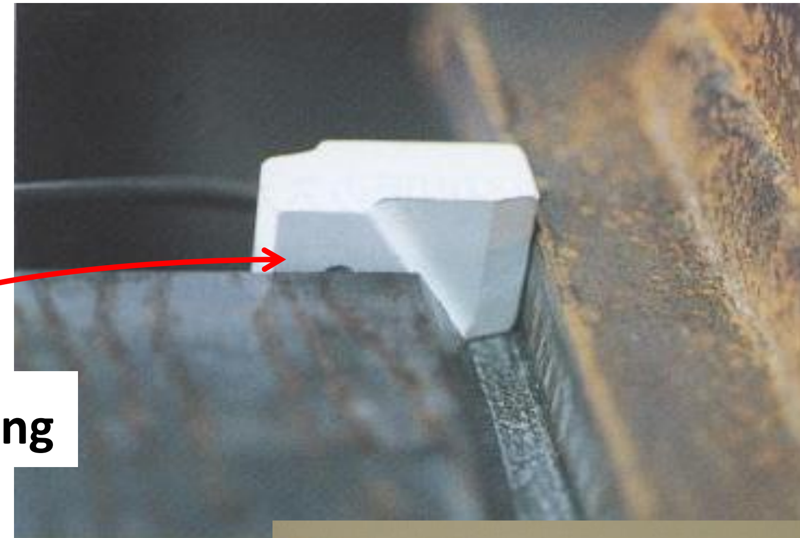


4) Improved type III (Non scallop)

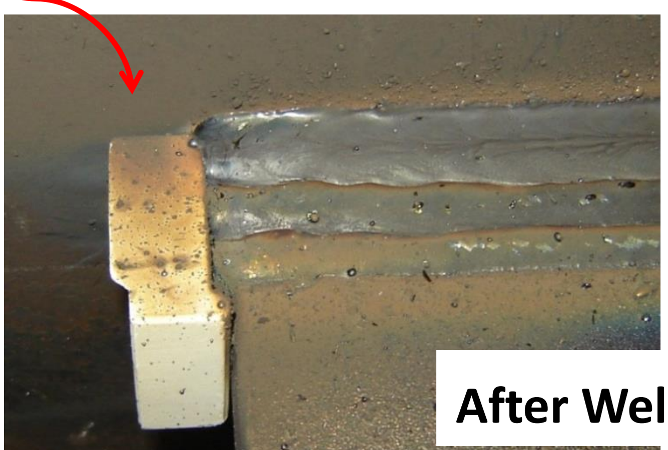
Run off tab requirements

Usage of ceramic run off tabs

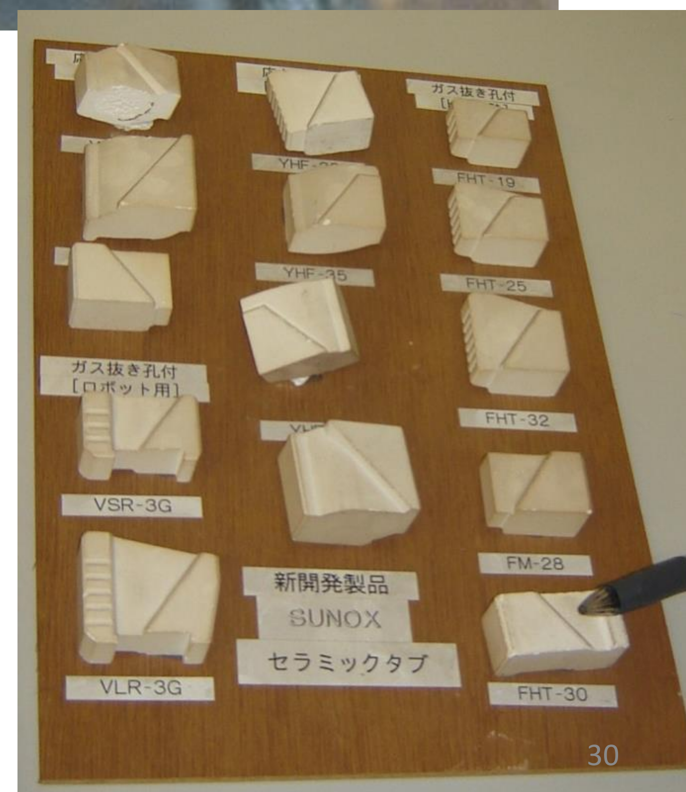




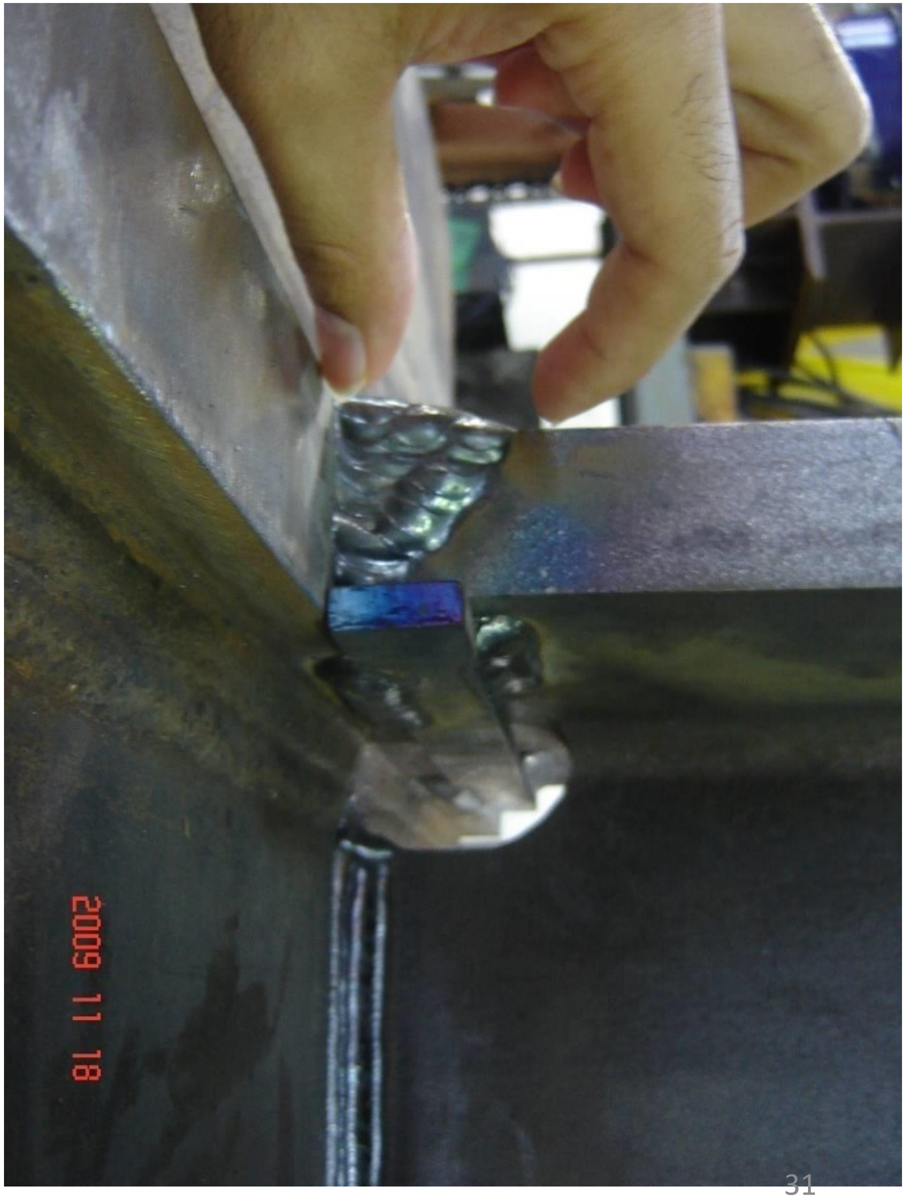
Before Welding



After Welding

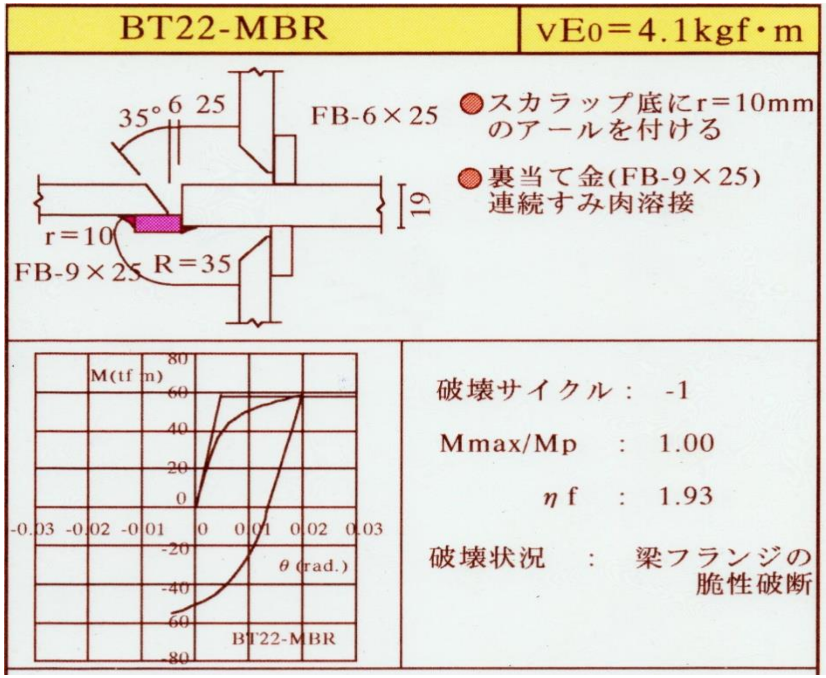


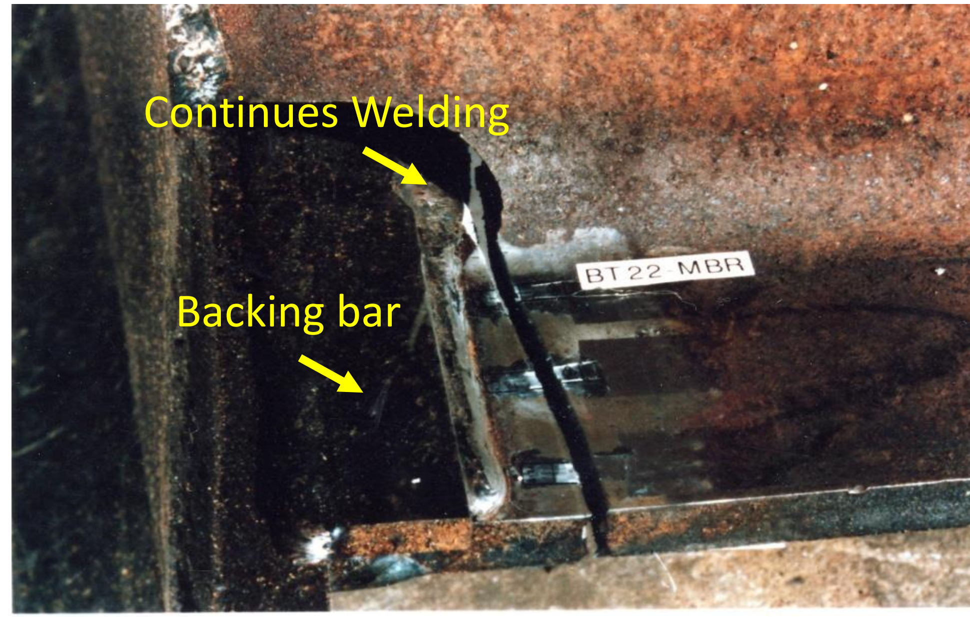
Usage of backing plates which are left in place

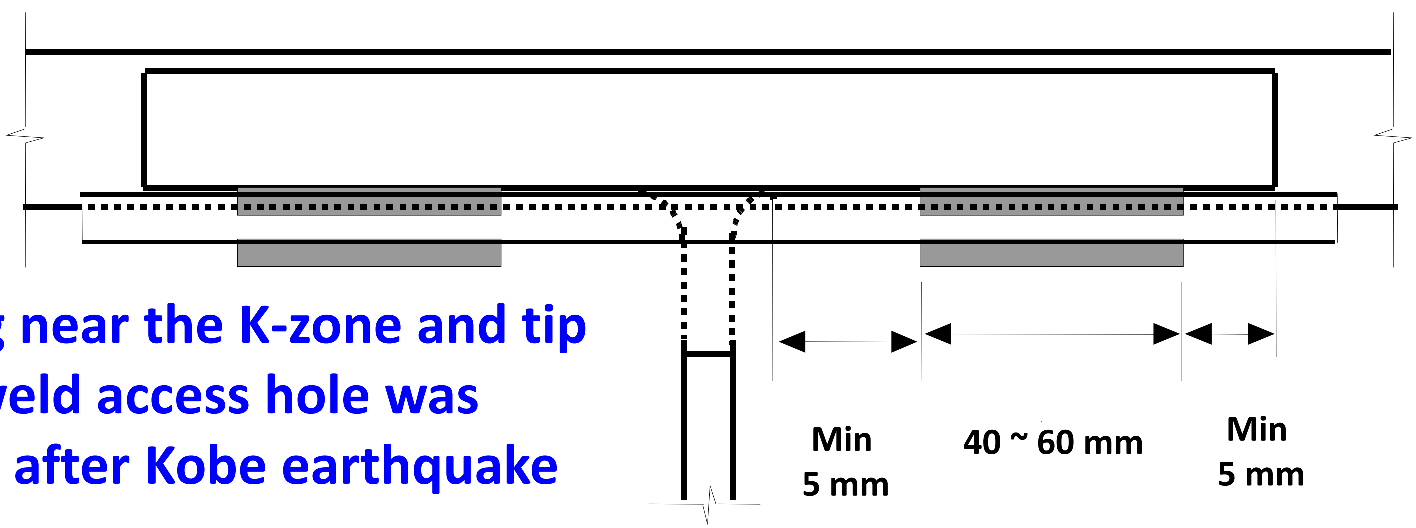


Effect of tack welding near the tip of weld access hole

Backing plate tack welding requirements





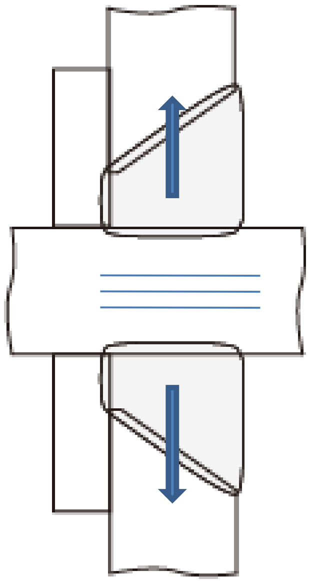


Welding near the K-zone and tip of the weld access hole was omitted after Kobe earthquake

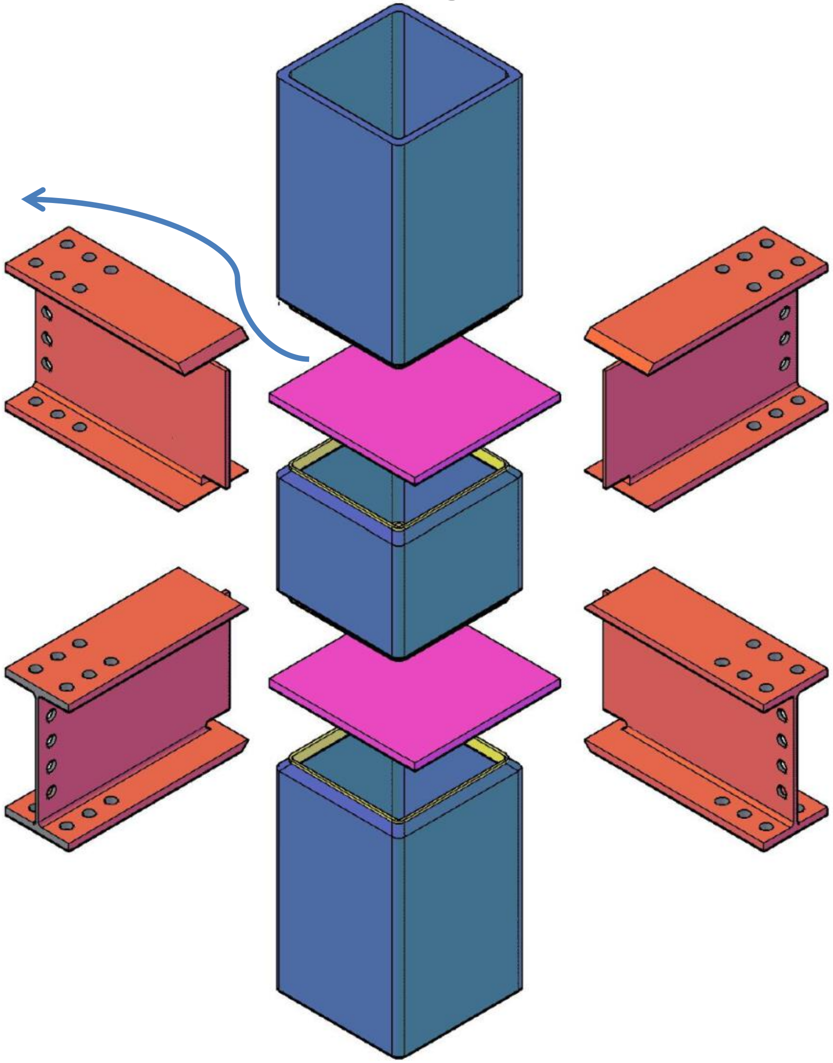
Diaphragm material requirements

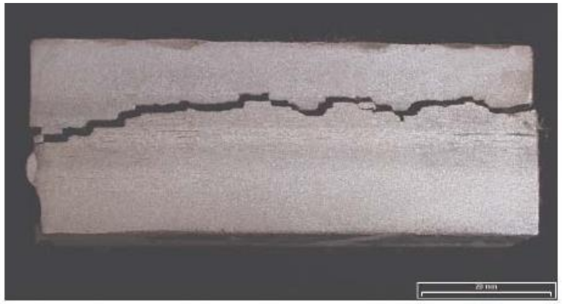
Control of sulfur content in production of material

Weld joint configuration increases the risk of lamellar tearing



Diaphragm





Lamellar tearing

Diaphragm material requirements

Control of sulfur content in production of C-grade material
SN 400C, SN490C

Grade	t(mm)	C	Si	Mn	P	S
SN400A	6≤t≤100	≤0.24	-	-	≤0.050	≤0.050
SN400B	6≤t≤50 50≤t≤100	≤0.20 ≤0.22	≤0.35	0.6~1.40	≤0.030	≤0.015
SN400C	16≤t≤50 50≤t≤100	≤0.20 ≤0.22	≤0.35	0.6~1.40	≤0.020	**≤0.008**
SN490B	6≤t≤50 50≤t≤100	≤0.18 ≤0.20	≤0.55	≤1.60	≤0.030	≤0.015
SN490C	16≤t≤50 50≤t≤100	≤0.18 ≤0.20	≤0.55	≤1.60	≤0.020	**≤0.008**

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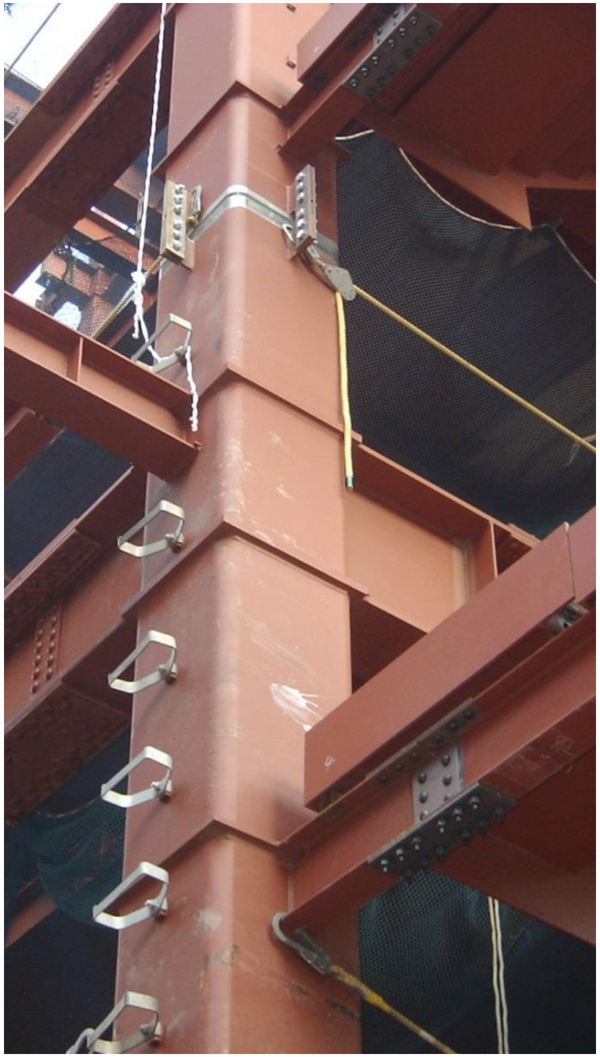
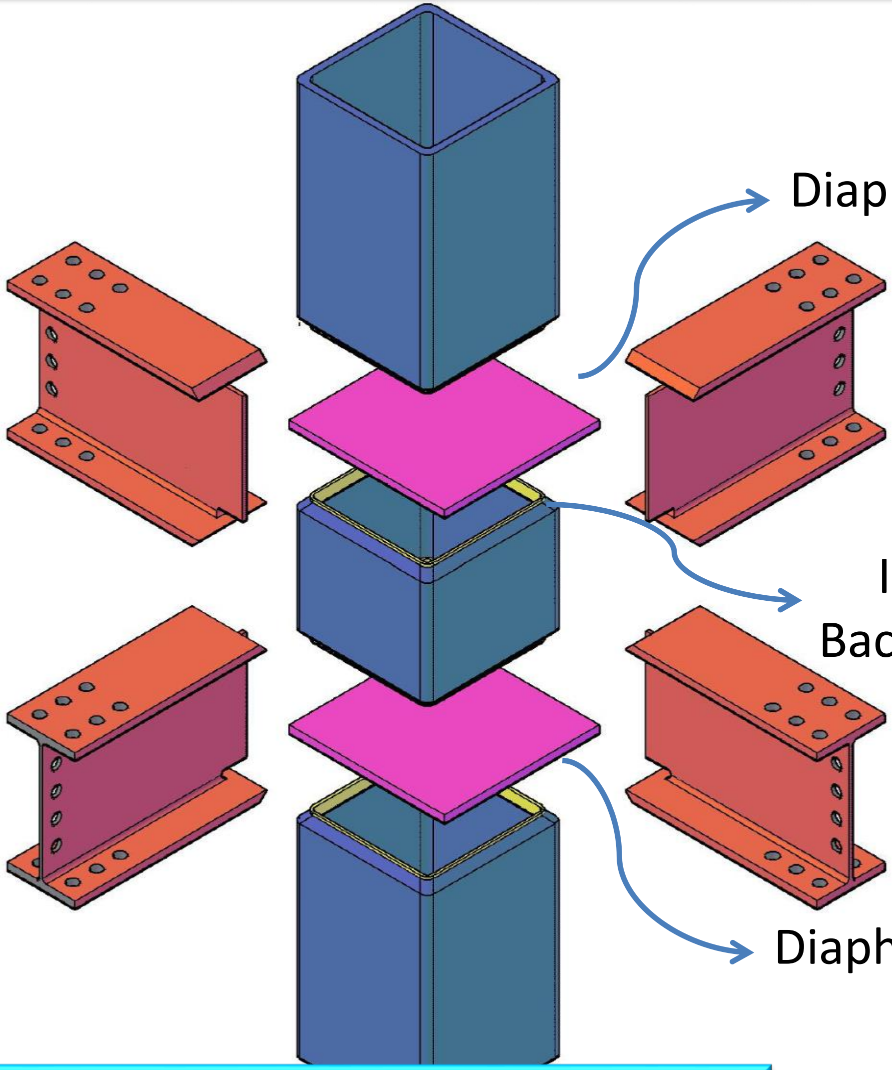
By application of mentioned requirements
Sufficient beam rotation capacity will be achieved





How about design??

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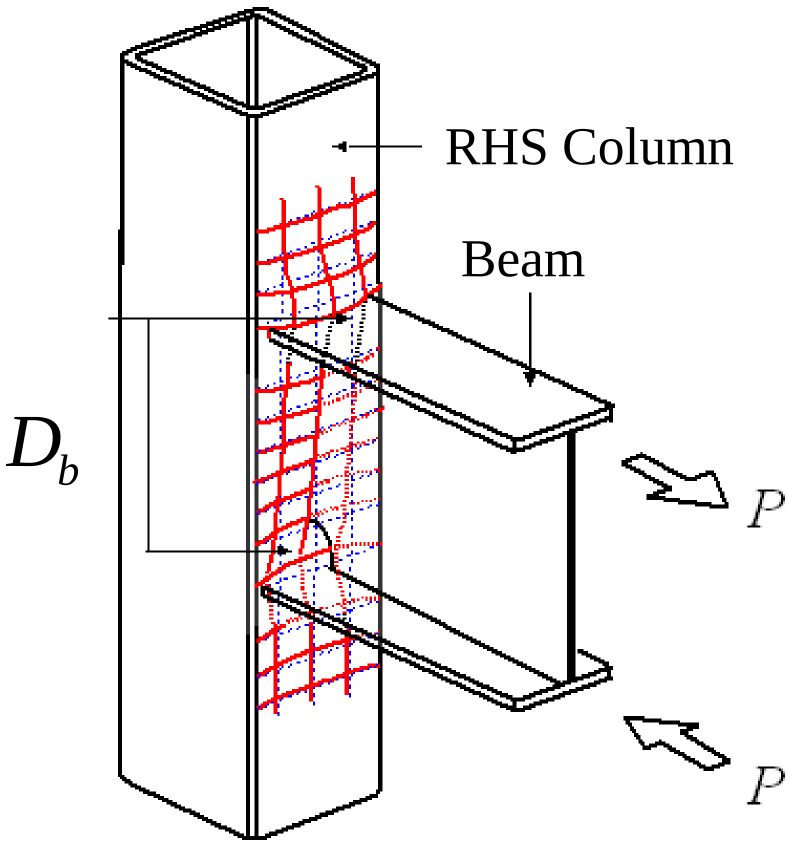
Design philosophy

- **Energy absorption Capacity > Input energy**
- **Connection** Roll is: Stress Transfer. So Rigidity, Strength , Ductility is expected.
- **Connection Capacity > Connecting Member Capacity**

- ***Design Concept :***

Connection Ultimate Capacity > α .(Plastic Capacity of Connecting Member)

Beam-to-box Column Connection

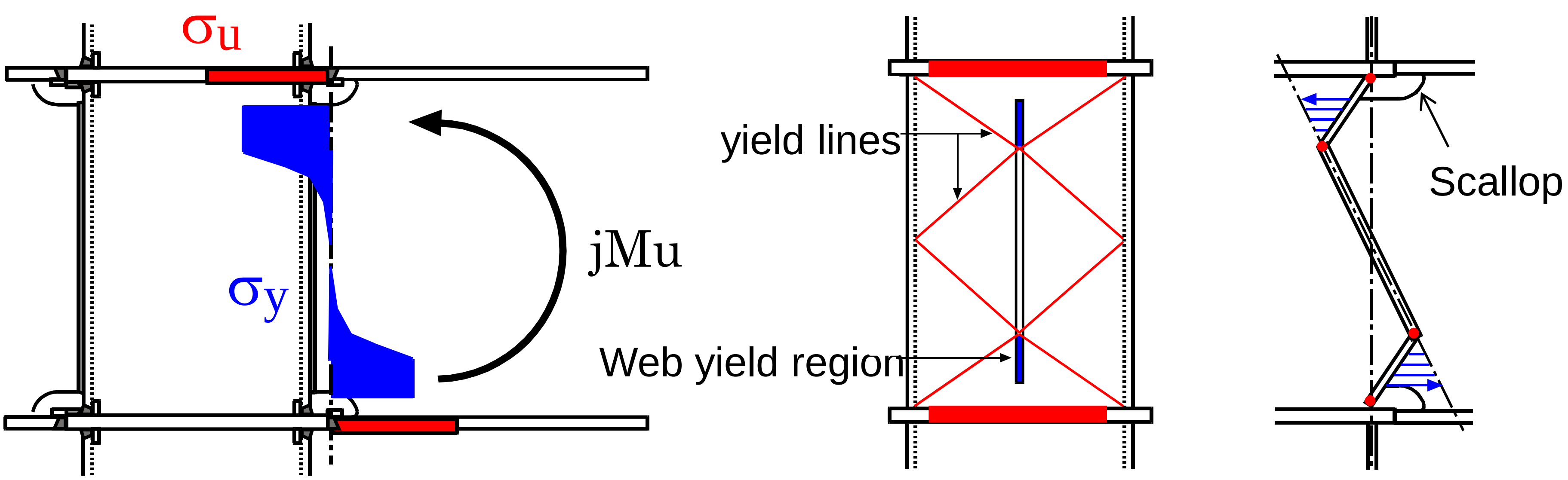


Coupling force acting at beam flange may cause significant **out of plain deformation**

- collapse mechanisms :

Out of plain deformation of column flange

Ultimate Flexural Capacity of Connection



$$ {}_jM_u = {}_jM_{fu} + {}_jM_{wu} \quad (1) $$

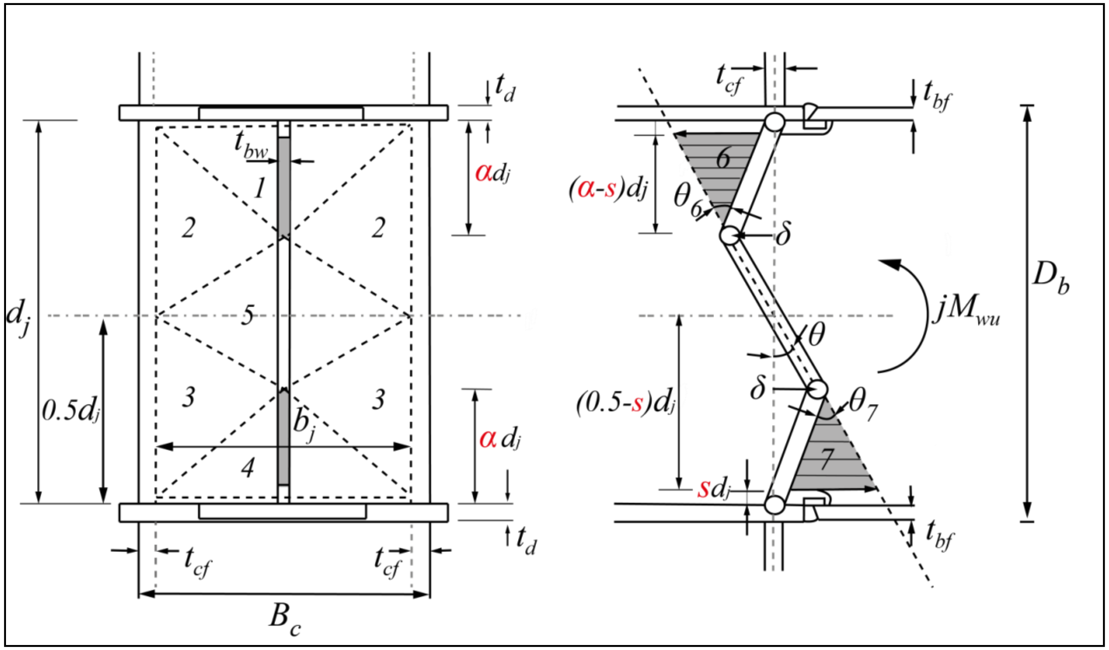
$$ {}_jM_{fu} : \text{Ultimate flexural strength of flanges} = A_f . d_b . \sigma_u \quad (2) $$

${}_jM_{wu}$: Ultimate flexural strength of web connection

$$ = m_0 . M_{wp} = m_0 . (\tfrac{1}{4} d_j^2 . t_{bw} . \sigma_y) \quad (3) $$

Ultimate flexural capacity of web connection

$$({}_jM_{wu})$$



AIJ
Recommendation for Design of Connections

$$ {}_jM_{wu} = m_0 . M_{wp} \qquad (4)$$

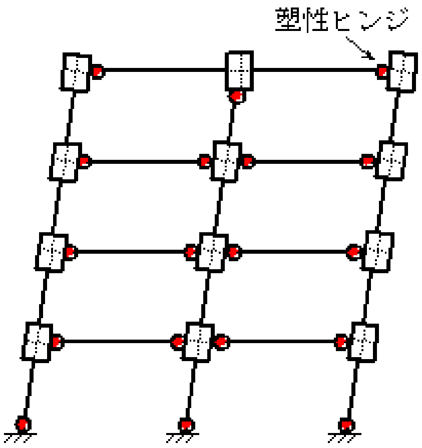
$$ m_0 = \frac{4}{kr^2}\sqrt{kr-4\sqrt{kr^3s^2+1}+\frac{4}{kr}-\frac{2}{kr^3}}-4s \qquad (5)$$

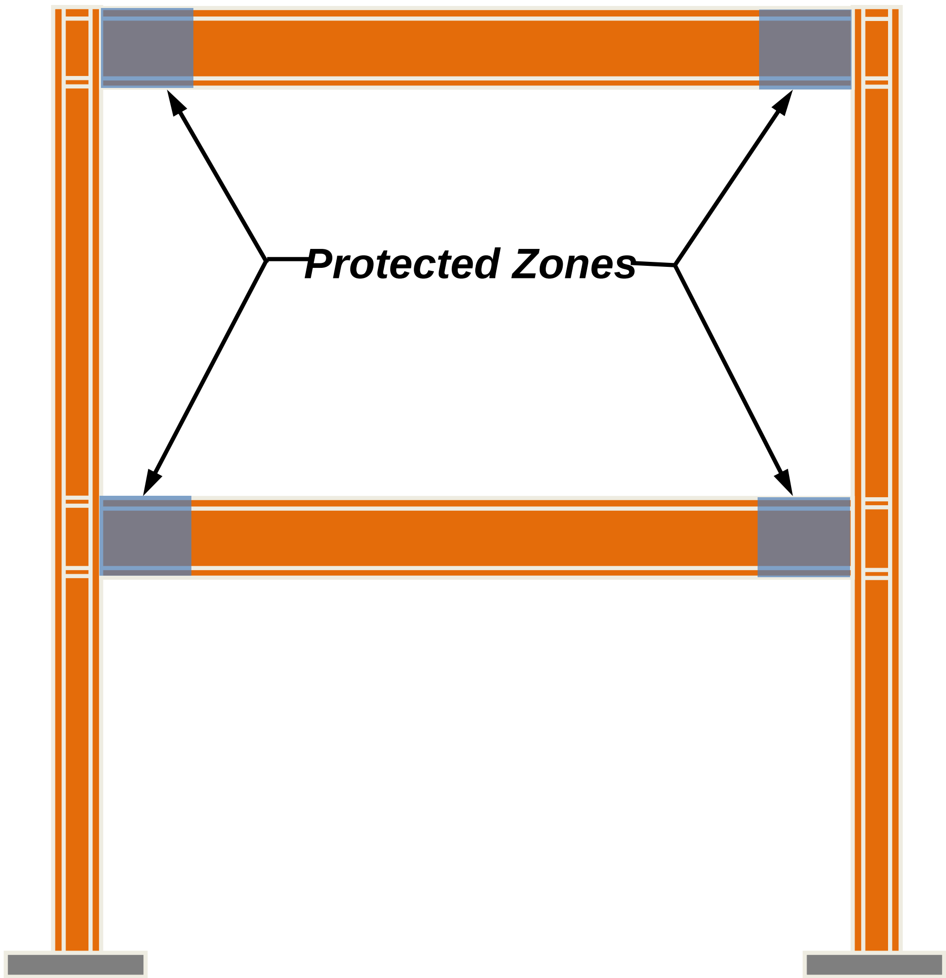
Where : $k = \left({b_j}/{t_{cf}}\right)^2\left({t_{bw}}/{d_j}\right)\left({\sigma_{by}}/{\sigma_{cy}}\right)$ (6) ; and $r = {d_j}/{b_j}$ (7)

Protected Zones

Designation of region at each end of SMF beam subjected to inelastic straining

Sensitive to welding , attachments, notches stud welding …





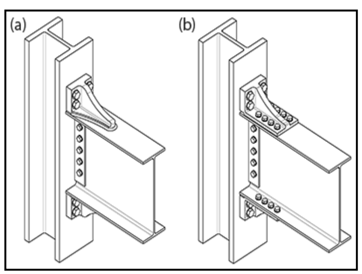
Protected Zones is Not introduced in AIJ

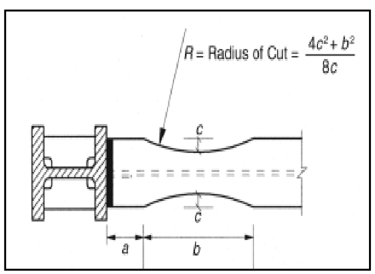
Connection

US : 1994 Northridge

could not provide plastic deformation
and
performed brittle fracture

different connection geometry & configuration
(mostly bolted connection types)



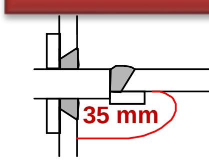


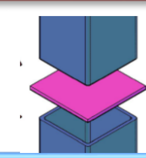
Japan: 1995 hyogoken-Nambu Earthquake

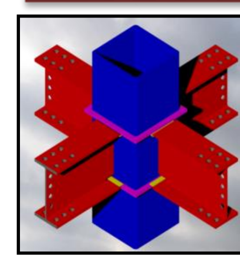
Premature fracture,
but
some plastic deformation before fracture

Try to use complete capacity of connection by improving:

- Detailing
- Quality Control
- Design

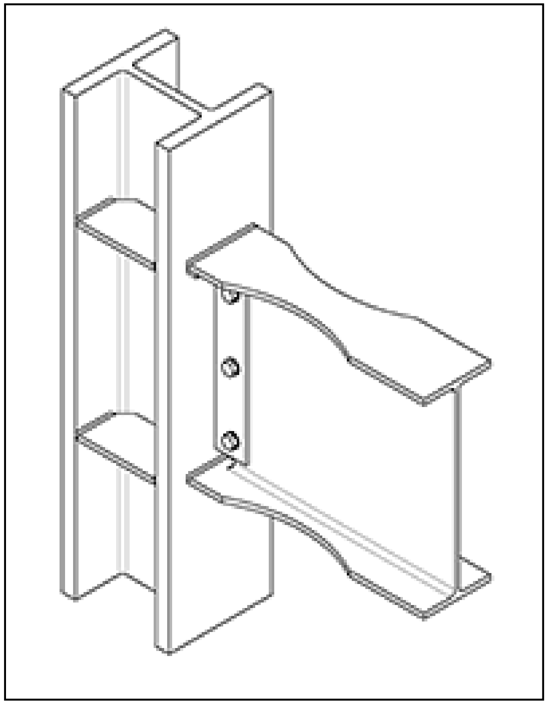


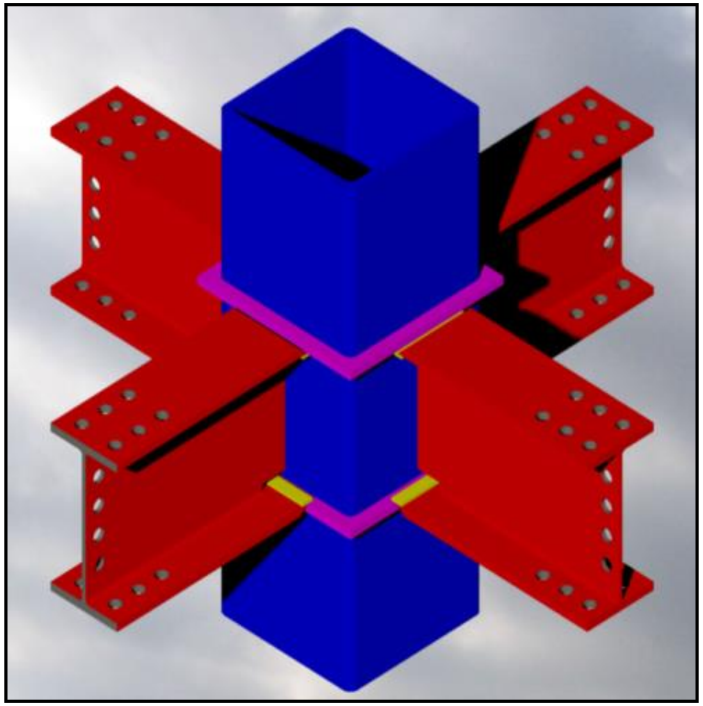




2 Different Approaches

Differences of Practice in US and Japan After Kobe Earthquake





Part 4:

- **Damage to Steel Buildings after 2011 Tohoku-Oki Earthquake in Japan**

Outline of Earthquake

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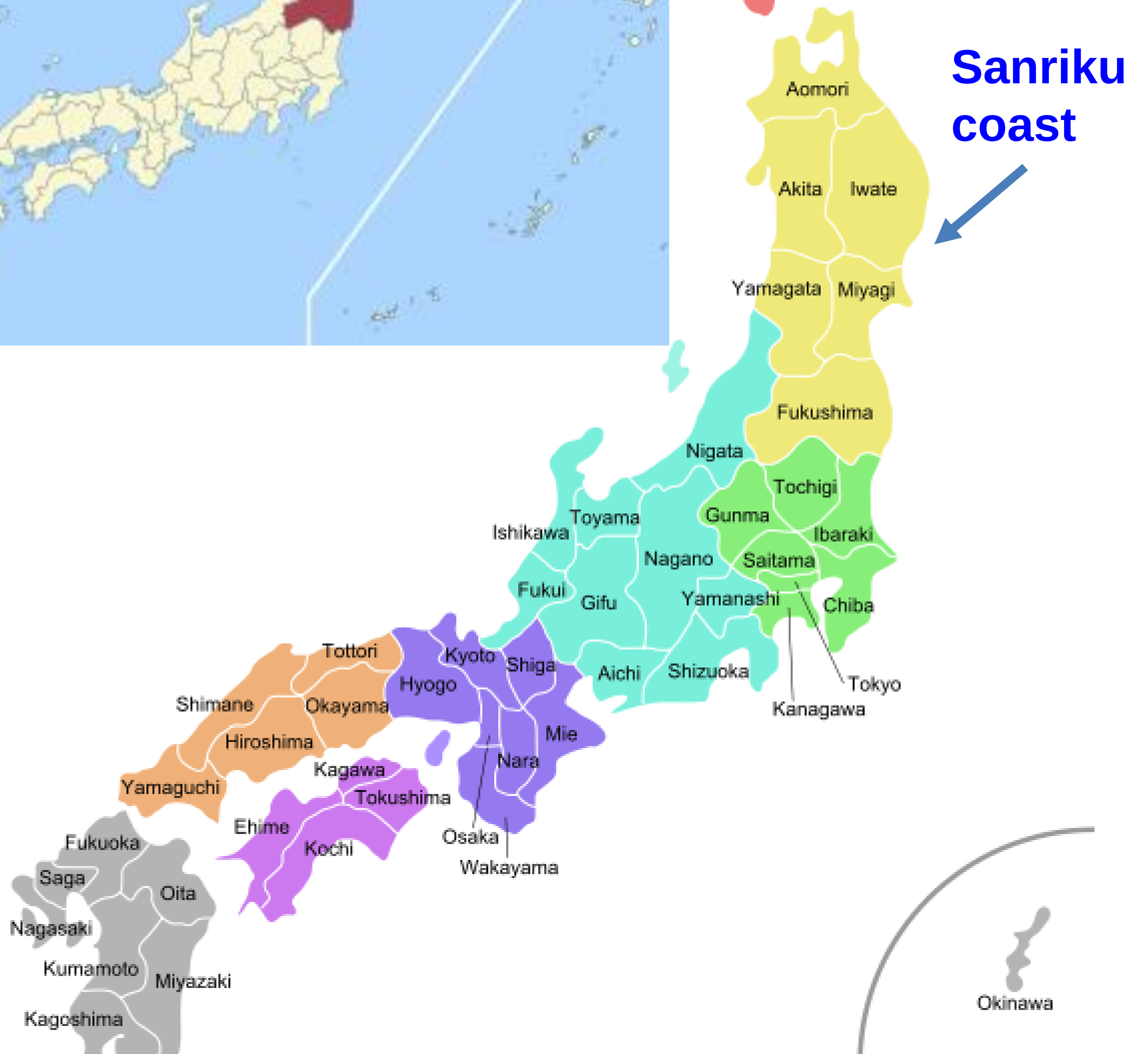
- Earthquake : March 11, 2011 at 14:46
- Name: The 2011 earthquake off the Pacific coast of Tōhoku (Tohoku-Oki)
- Magnitude:9.0, Depth:24km
- JMA Intensity: 7(1 areas), 6+(34 areas),6-(70 areas)
- Tsunami: March 11,2011.14:49
- Tsunami max. observed hight:15m
- Death:15,073,Unknowm:8,657,Injured : 5,472
- Completely damaged house:102,973, Others:312,998
- Fire:313
- Evacuation:158,738
- Other damage: Infrastructures (Road, Railway, Port), Factory, Fisher, Agriculture, Forest, etc.)



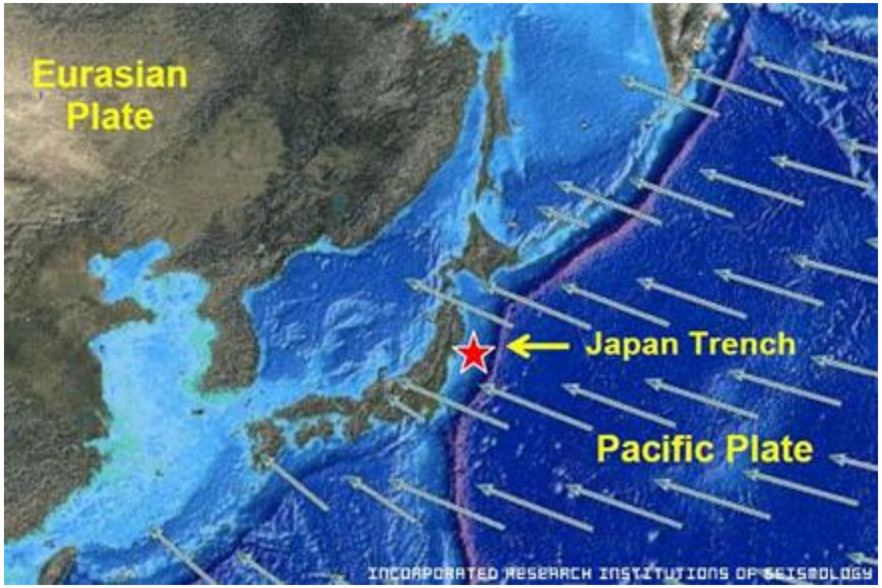
Tohoku: one of the most seismically active regions in Japan

The Mw 7.7, **1978** Miyagi earthquake claimed 27 lives and damaged thousands of buildings including a number of steel buildings

14:46 on 11 March 2011 a magnitude (Mw) 9.0 earthquake occurred off the Sanriku coast of Japan

Severe ground motion was recorded over the prefectures of Iwate, Miyagi, Fukushima, and Ibaraki

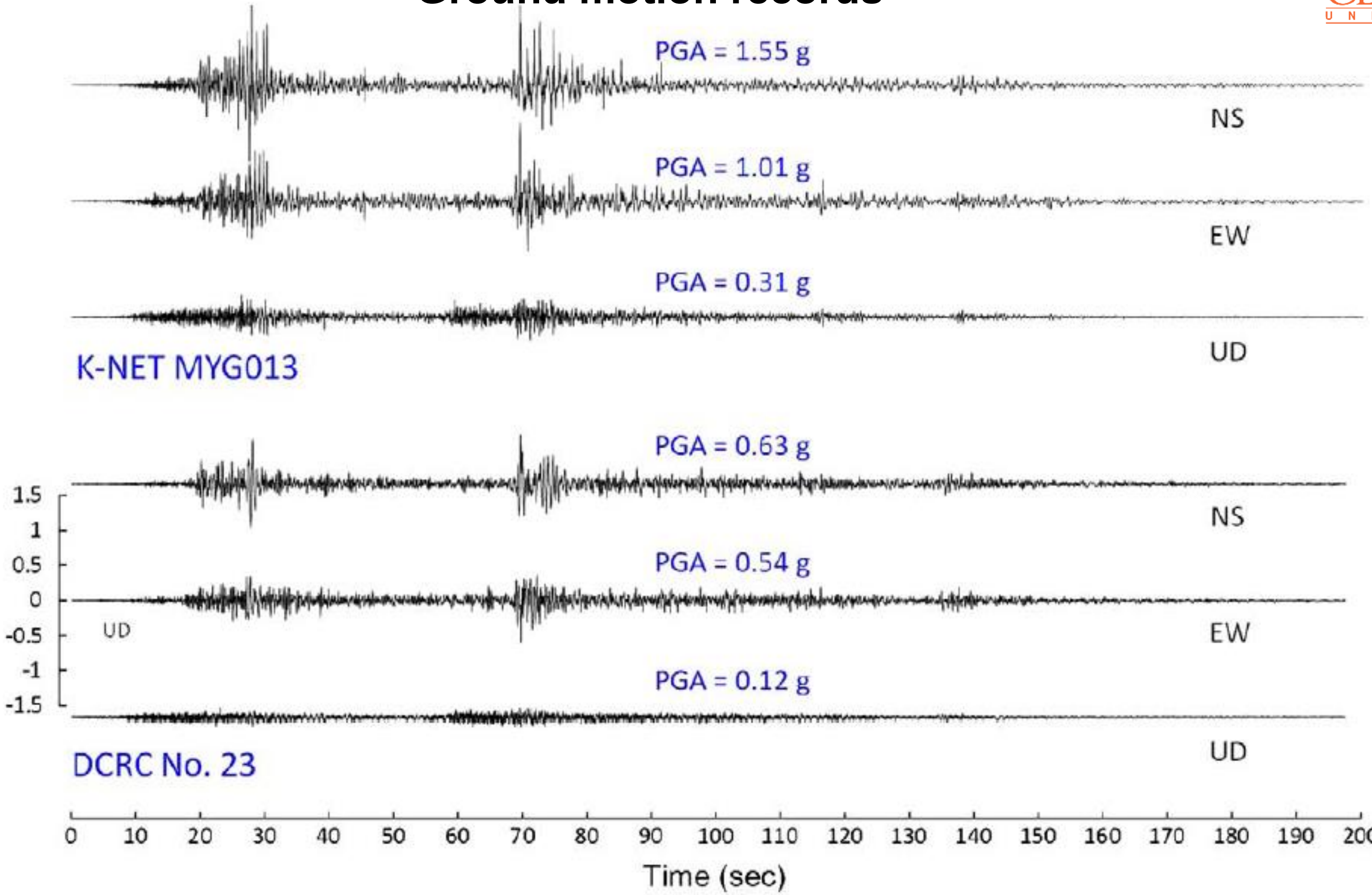
- Very limited damage due to ground motion effects, but tsunami effects was destructive



- The 2011 Tohoku-oki earthquake produced the **first major tsunami that attacked these industrialized ports**

- Tohoku coast experienced a multitude of **destructive effects**: severe ground motion, liquefaction, foundation scour, large lateral load produced by tsunami pressure, debris delivered by tsunami, and fire.

Ground motion records

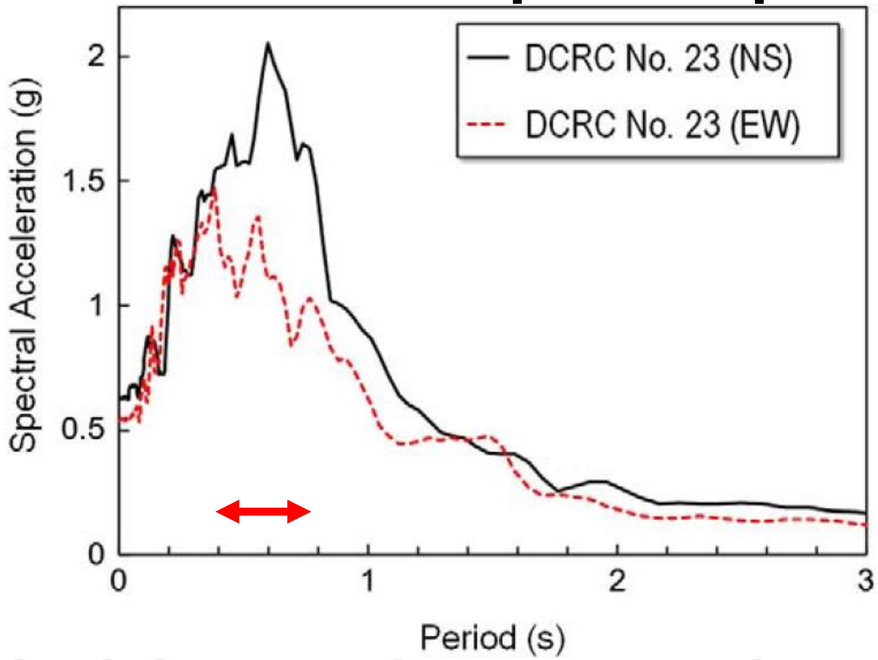


2 recording stations: MYG013 & 23 Tohoku University (DCRC) in Oroshimachi district

Ground acceleration history record suggest:

- **Duration of strong motion exceeded 2 minutes**
- **2 separate strong motion arrived less than 1 min. apart**
- **MYG013 record shows extremely larg PGA exceeded 1.5g in N-S component**

Acceleration response spectra

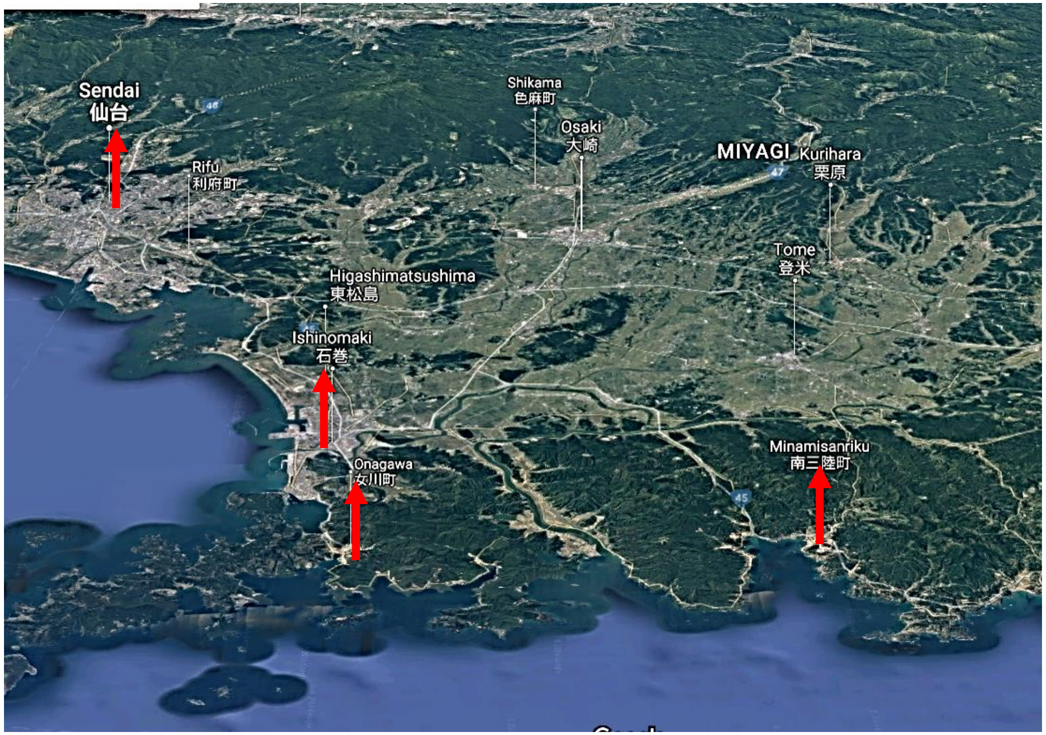


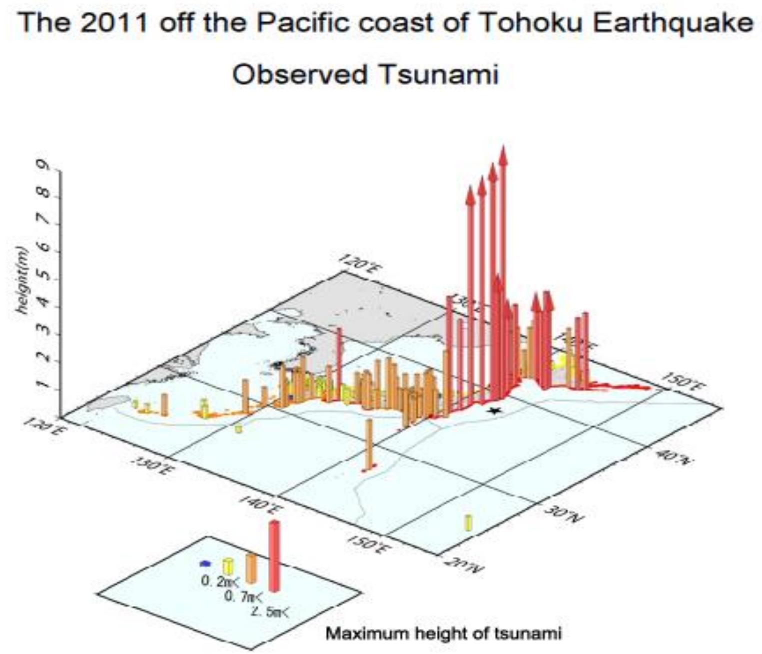
Very limited damage due to ground motion effects (Examined by Hokkaido University reconnaissance team)

- Ground motion had its **principal period between 0.5** s **and 0.8** s, and **was not particularly strong in the 1 s to 2 s period** range that tends to produce the most destructive effects on steel structures.
- Reconnaissance findings indicate that steel structures performed well under this ground motion.

Reconnaissance team from Kobe University:
Earthquake and Tsunami effects of the 2011 Tohoku-oki earthquake were examined at 4 coastal locations:

- **Minamisanriku**,
- **Onagawa,**
- **Ishinomaki,**
- **Sendai port**.





The port of Sendai is the largest transportation hub in northeast Japan

Onagawa is a fishing port where the tsunami reached an extreme height 15 m.

Minamisanriku (南三陸町) :
Towen in the Motoyoshi District of Miyagi Prefecture
95% of the town was destroyed by the

- **A large number and a large variety of steel structures were attacked by the massive tsunami**
- **In most cases, claddings were completely washed away by the tsunami, structural damage was limited**

- **Minamisanriku Disaster Mitigation Steel building**
- **One by two-bay,**
- **Three-story MRF**
- **Evidence of sever debris impact**

Steel buildings stood upright after the tsunami subsided. However, in most cases, steel buildings suffered extensive damage to their external and internal finishes along with their contents

No structural damage


防災対策庁舎

Minamisanriku's disaster Management Building, a symbol for the disaster and recovery

Iwanuma (岩沼市, *Iwanuma-shi*) is a city located in Miyagi Prefecture.
As of July 1, 2010, the city has an estimated population of 44,379 and a population density of 731 persons per km². The total area is 60.71 km².
Iwanuma is home to the Takekoma Inari Shrine, the second-oldest shrine dedicated to the *kami* Inari.
It was seriously affected by the tsunami associated with the 2011 Tōhoku earthquake.

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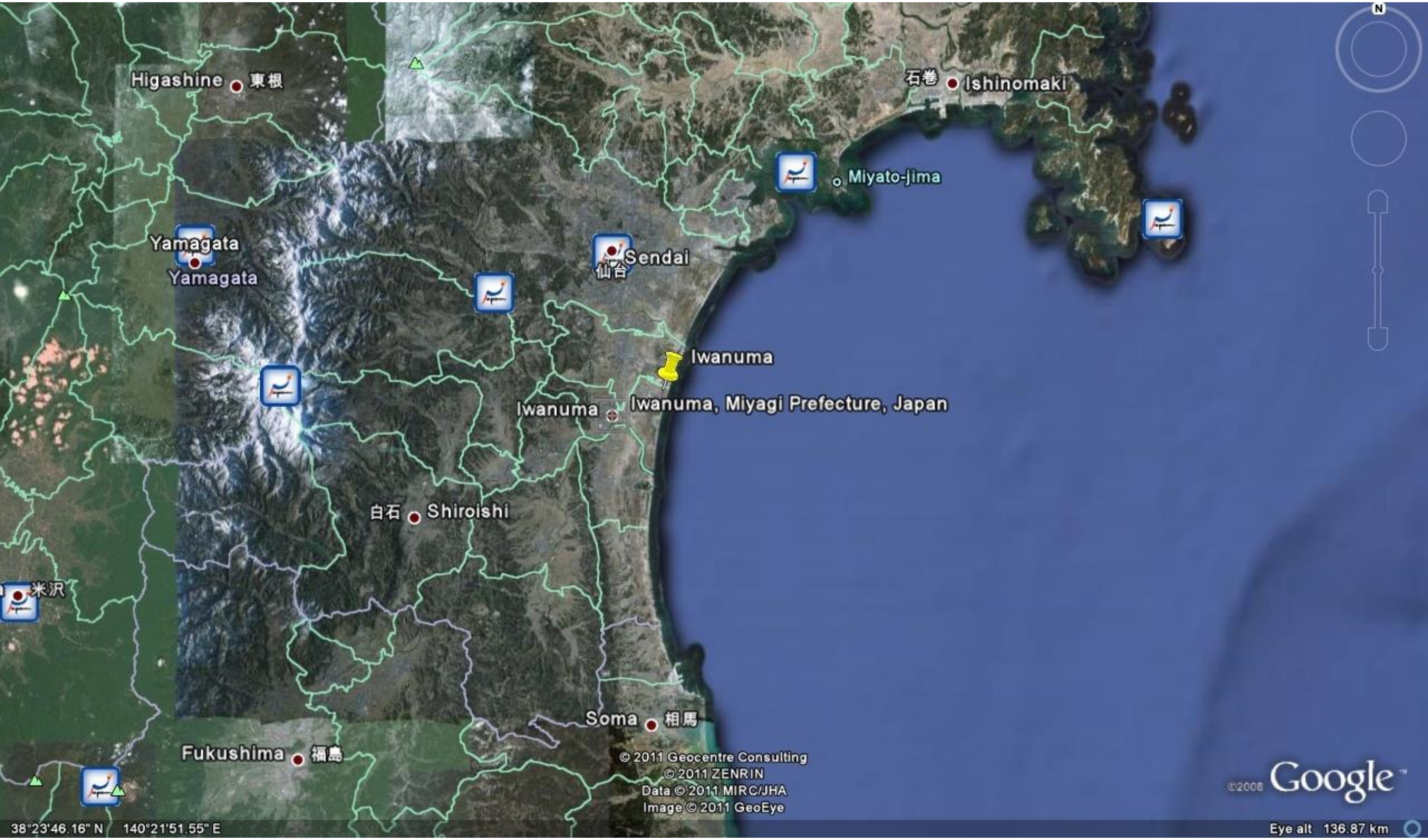

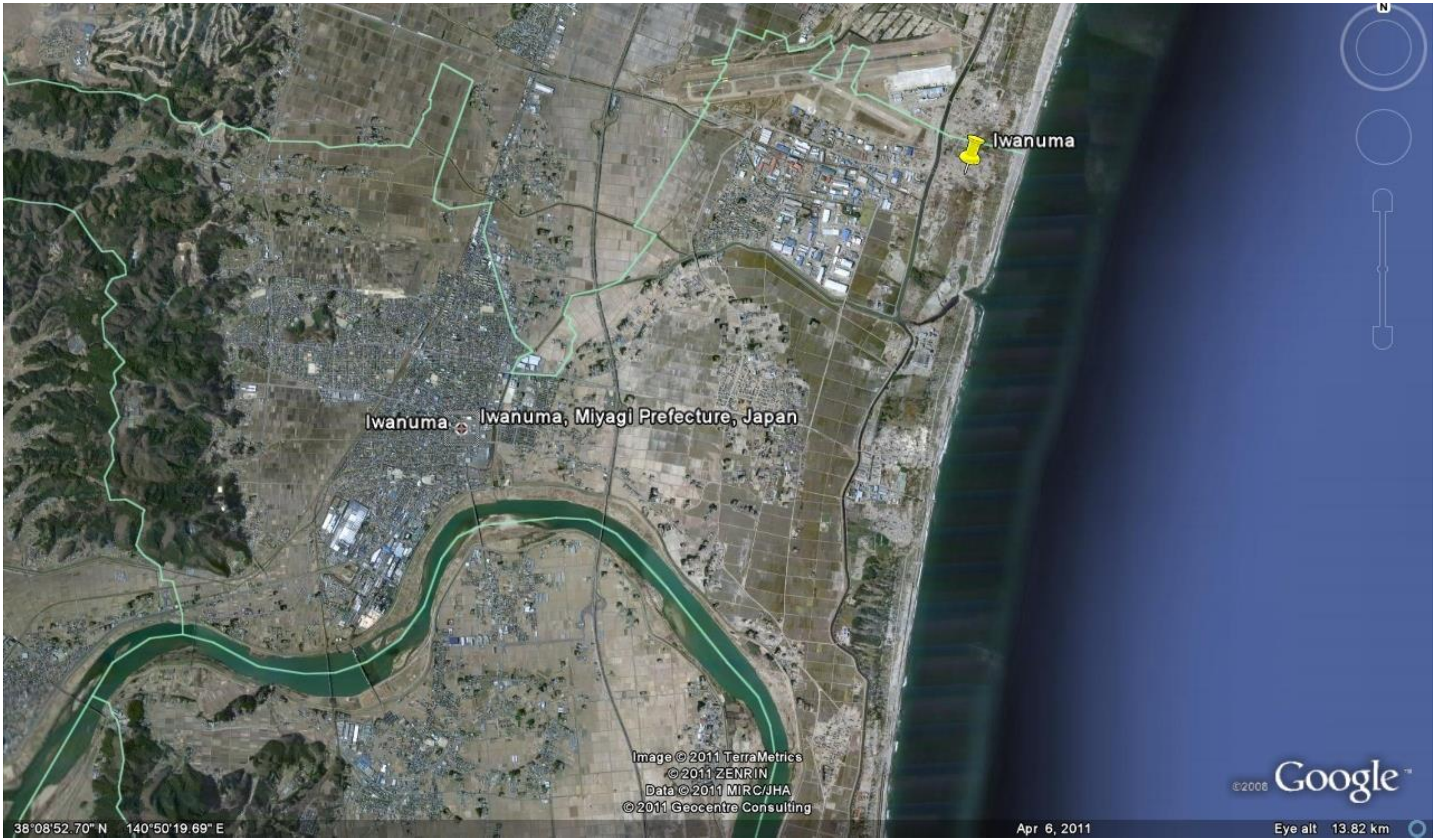
Iwanuma
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Iwanuma, Miyagi Prefecture, Japan
Image © 2011 TerraMetrics
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©2008 Google
38°08'52.70" N 140°50'19.69" E
Apr 6, 2011
Eye alt 13.82 km

- Residential area between airport and shoreline was completely destroyed by tsunami
- Due to failure of seawall, tsunami attacked Sendai airport 1000 m from the shore.

- The area was densely populated with timber residences.
- Almost all of timber residences were completely destroyed by tsunami
- **Jus light-gauge steel residence that stood upright but suffered extensive damage to its exterior and contents**

- **Two-story residence constructed with steel in the first story and timber in the upper story**
- **The exterior wall was lost at the first floor**


5 5 2011

- The external claddings in these structures were easily damaged by tsunami
- It is suspected that the early loss of claddings, alleviated the immense lateral load that the tsunami pressure otherwise would have delivered

No structural damage in the steel frame

Onagawa (女川町*Onagawa-ch .): is a town located in Miyagi perfecture.*

The town was heavily damaged in the 11 March 2011 Tohoku earthquake and tsunami. **The tsunami reached 15 meters in height** and swept one and half kilometer inland, destroying the town centre and leaving over 1000 people missing, with over 300 confirmed dead. At least 12 of the town's 25 designated evacuation sites were inundated by the tsunami.


Google


4 5 2011

•Two-story residence constructed with steel in the first story and timber in the upper story

•The upper timber story and exterior wall of first story was lost

No structural damage in the steel frame

Steel structure just near by the coast of Onagawa


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The exterior wall was lost;
Steel structure could withstand large tsunami forces


4 5 2011

The strength of the column base seemed to play a key role in collapse prevention against the tsunami

Conclusion

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- Reviwe on Post-Kobe earthquake researches showed different approach of connection design in Japan

- Tsunami effects were studied in Minamisanriku, Onagawa, Ishinomaki and Sendai.

- Reconnaissance findings indicate that steel structures performed well under ground motion; Post-Kobe earthquake researches resulted in the significant improvement of steel moment frame buildings behavior.

- Steel buildings designed according to the current Japanese standards may withstand large tsunami forces but they are not likely to provide safe shelter for tsunami evacuation when the building submerges under tsunami wave.

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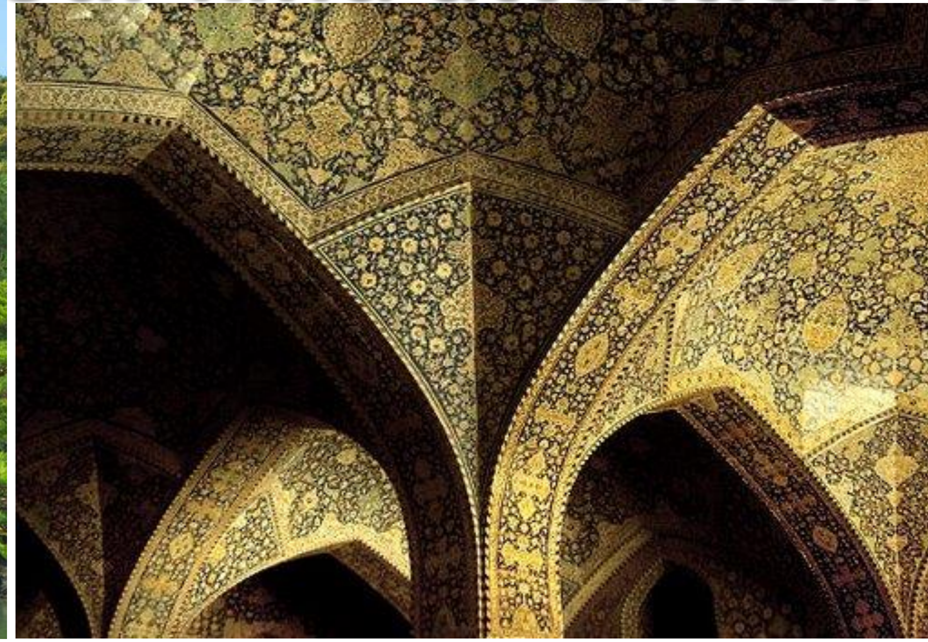
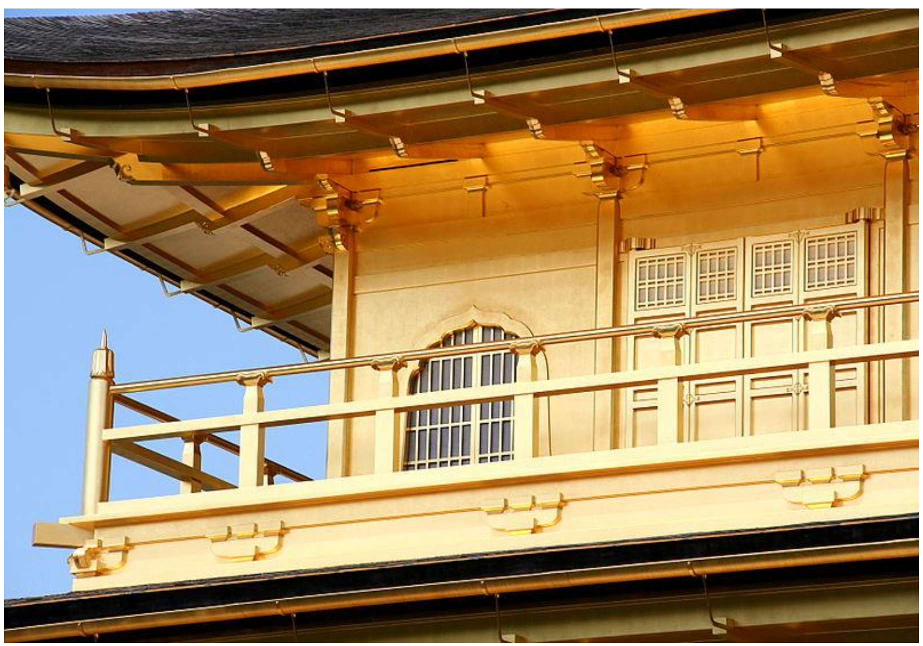
I appreciate your kind attention





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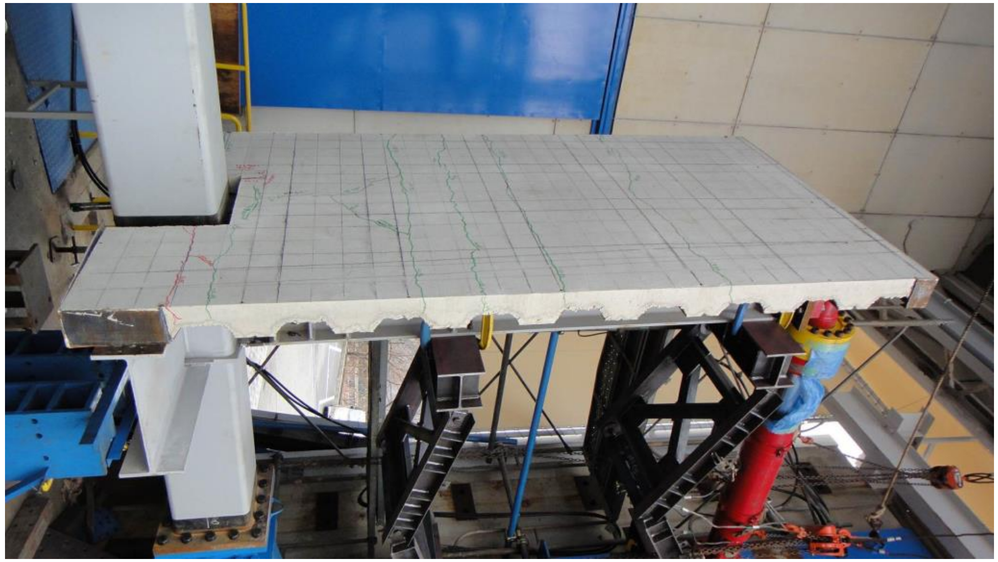
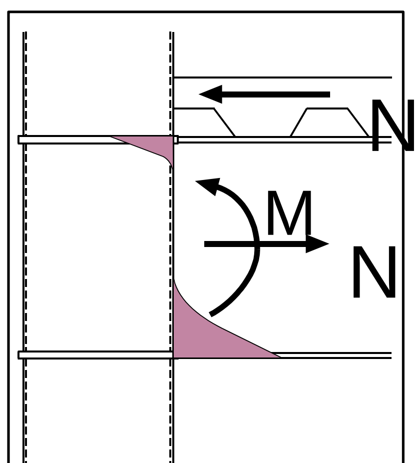
Seismic Behavior of Composite Beam Connected to box Column

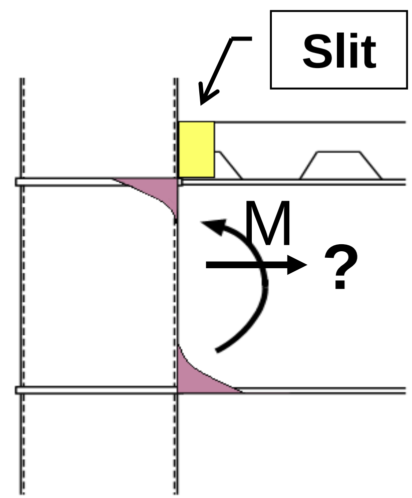


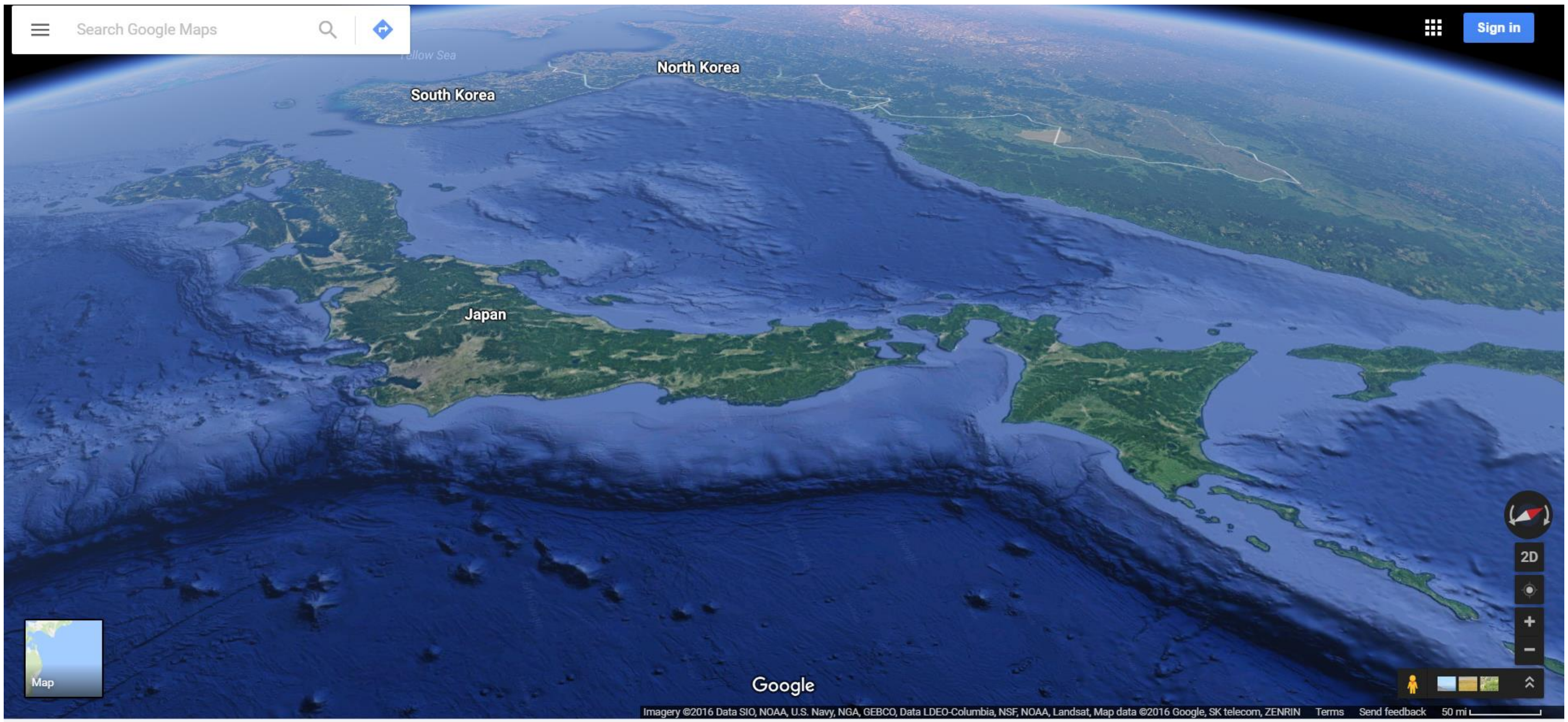
Providing a slit between the slab and column face is proposed by AISC.

Not recommended in AIJ

Eliminating the transmitted compressive force of slab from the column→relaxation of the lower flange strain can be expected.



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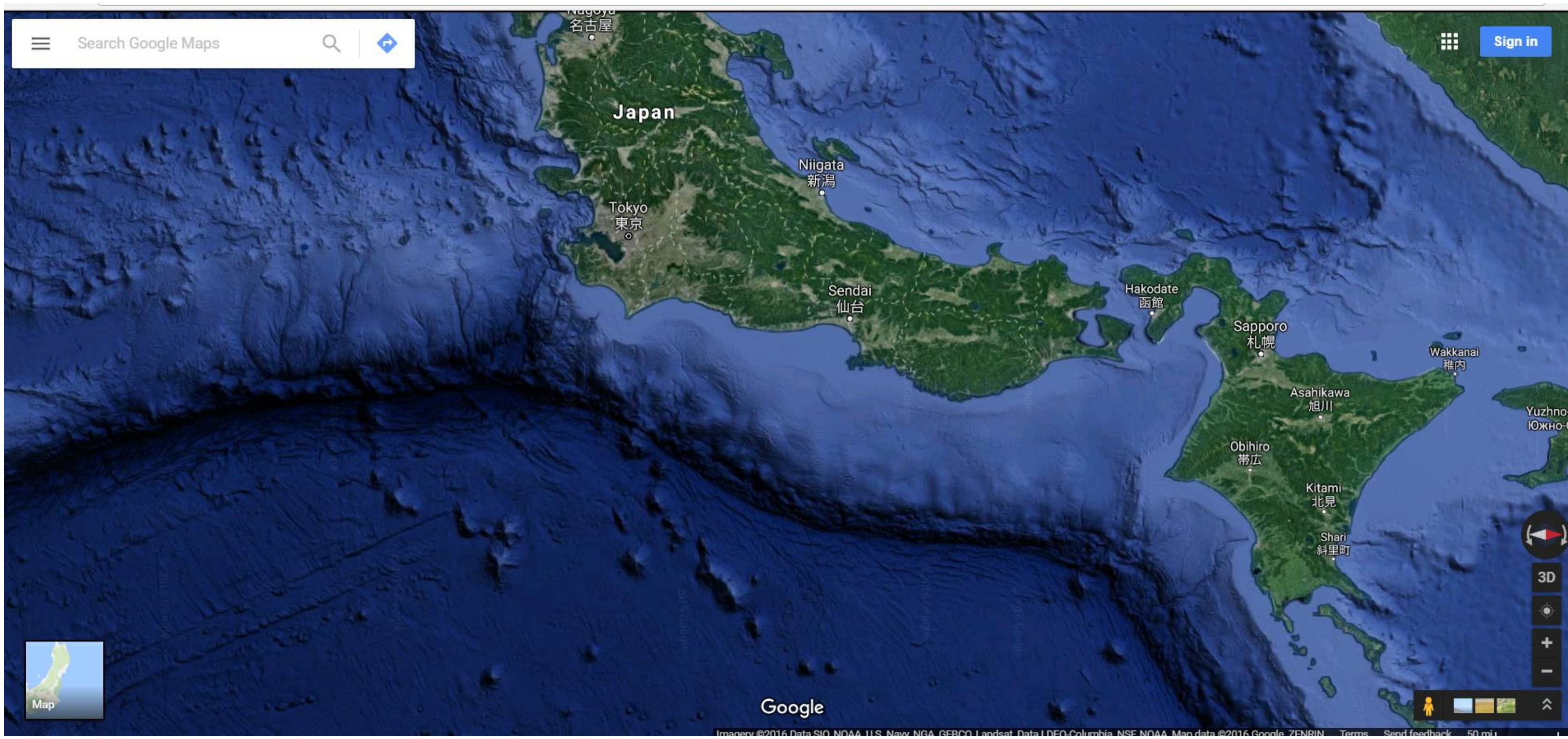
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