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Review of Damage in Welded Joints Caused by The Kobe Earthquake†

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Abstract

"The Kobe Earthquake" struck on January 17, 1995, and caused considerable damage in the Hanshin area. In recent earthquakes in Japan, performance of steel structures has been fairly good, but subject to the Kobe Earthquake, variable types of new damage are found among steel structures. In the present paper, damage in steel structures, especially damage at welded joints, is reviewed from some investigation reports and articles. Some of the investigation reports are listed at the end of this paper.

KEY WORDS: (Damage due to earthquake) (Steel structures) (Welded joints) (Brittle fractures)

1. Introduction

"The Kobe Earthquake" (magnitude of 7.2 on the Richter scale) that struck at 5:46:52 in the morning of January 17, 1995, caused considerable and variable types of damage in the Hanshin area (around Kobe and Osaka). It was one of the largest earthquakes in Japan since "The Great Kanto Earthquake" of 1923 (magnitude of 7.9).

Just after the earthquake, many official institutions, academic organizations, universities, societies and private companies made reconnaissance and research. Reports and some considerations about damage due to the earthquake have been presented.

In this review, an outline of the damage in steel structures, especially damage at welded joints, is given from some investigation reports and articles. Investigations, mainly describing steel structures, and published up to the present by official institutions and academic organizations, are listed at the end of this paper.

The name of the earthquake was officially given by the Japan Meteorological Agency as "The Hyogoken-Nanbu Earthquake". But, as the extent of damage, scale and social upheaval caused by this earthquake was revealed by intensive media coverage and investigations following this earthquake, the term "The Great Hanshin(-Awaji) Earthquake Disaster" is also widely used. But, in this review "The Kobe Earthquake" is used, because of simplicity and world-wide familiarity with the name of "Kobe".

2. An outline of the earthquake and damage[1),2),3),4),5),6)]

The epicenter was located in "The Nojima Fault", Latitude=34º36.4'N, Longitude=135º2.6'E, and the focal depth was 20km (**Fig.1**). About 6,000 people were killed and about 300,000 buildings, many bridges, viaducts for highways and railways, port facilities and other structures were damaged. It was guessed that many of the dead were lost through the collapse of houses and nearly 90 percent of these houses were composed of wood members.

The characteristics of the earthquake are a brief duration of vibration followed by large ground motions. The acceleration record of the earthquake, recorded at the

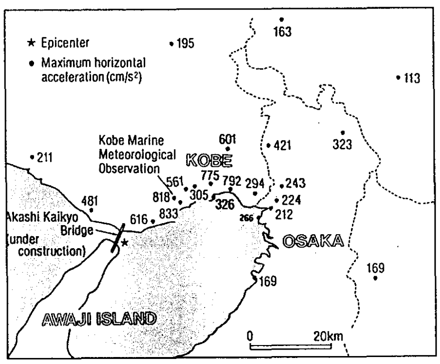

Fig.1 Epicenter of The Kobe Earthquake and maximum horizontal acceleration.[10)]

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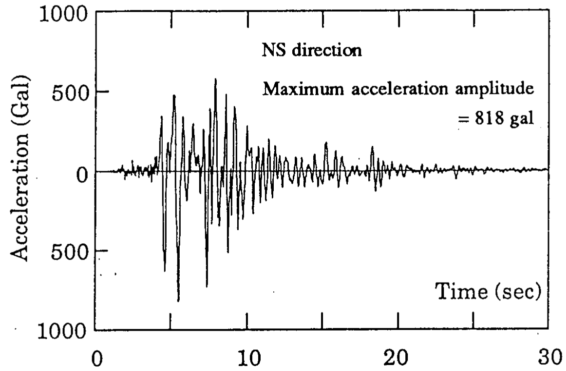

Fig.2 The acceleration record at the Kobe Meteorological Observatory[6)]

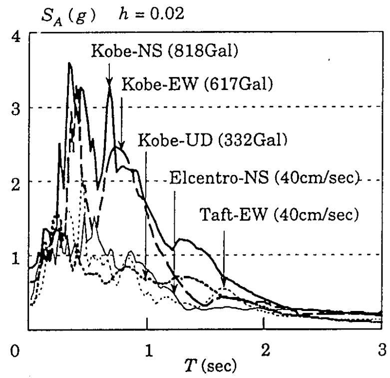

Fig.3(a) The acceleration response spectrum.[6)]

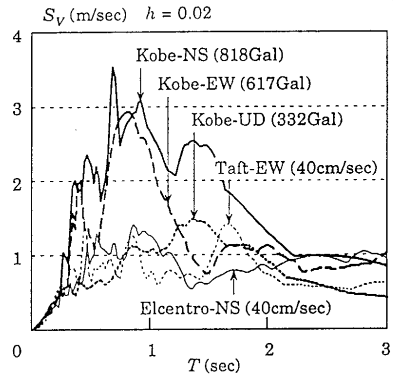

Fig.3(b) The pseudo velocity response spectrum.[6)]

Kobe Meteorological Observatory (about 15km away from the epicenter), is shown in **Fig.2**. **Fig.3(a)(b)** show the acceleration response spectrum and the pseudo velocity response spectrum calculated from the record. The peak acceleration is over 800 gal, and strong shaking lasted only 10 seconds. These indicate that the seismic force was large and could cause damage to structures within one cycle of vibration. The acceleration response spectrum of the El-Centro (NS 1940) and Taft (EW 1952) are also shown in Fig.2, both of which are usually used as the structural design spectrum for high-rise buildings in Japan. It suggests that the acceleration response spectrum and the pseudo velocity response spectrum of the Kobe Earthquake are much larger than these design spectrum. The maximum velocity and displacement are reported as 104kine and 27cm. In spite of these large records of vibration, the surroundings of the Kobe Meteorological Observatory had little damage.

For the large earthquake, surveyed above, occurring near the crowded modern city, considerable damage might be caused.

3. Damage in steel structures [7)]

In recent earthquakes in Japan, the performance of steel structures has been fairly good due to ductile material properties. However, subjected to the Kobe Earthquake, variable types of new damage are found among steel structures.

3.1. Steel Viaducts and Bridges [7),8),9),10)]

Only 2 steel piers completely collapsed and this number is much less than for RC piers. At first these piers cracked at a welded corner, and then these collapsed a few hours after the earthquake like peeling banana **(Fig.4)**. It is guessed that the cause of the collapse was due to an increase of dead load by collapse of neighboring RC piers, but the exact causes are unknown. Other types of damage, local buckling, cracks due to local buckling in circular piers **(Fig.5)**, cracks due to low cycle fatigue at beam-column connections and brittle fractures of circular piers made with centrifugal casts **(Fig.6)**, were observed in piers . Cracks due to low cycle fatigue also may appear in welded connections between base-plate and pier, when encased concrete around these connections is destroyed in the future.

Upper structures showed little primary damage. Many of them were secondary damage caused by fall-down of girders due to horizontal displacement, movement or sudden collapse of piers.

In the other parts, failure and fall-down of cast bearings, failure of expansion joints and fractures of splice plates or bolts, were found.

Just near the epicenter, the longest bridge in the world, "Akashi-Kaikyo Bridge" (full length =3,910m center span =1,990m), was under construction (Fig.1). When the earthquake occurred, the erection of the towers of the bridge, which are about 300m tall, was complete, all the cable strands were placed and cable squeezing work was in progress. At the top of towers, large seismic accelerations, more than gravity accelerations, were experienced due to the earthquake. After the earthquake, the relative displacements of the bridge were measured. As the result of the measurement, the Awaji Island side tower and anchorage moved about 1.3m relative to the Kobe side tower and anchorage. Then the center span length, originally 1,990m, was increased to 1,990.8m (**Fig.7**). But, it was fortunately found that the earthquake caused no critical damage to the bridge. The elongation of the span will be accomplished by adjusting the length of some panels of the stiffening girder.

3.2. Steel buildings [6),11)]

In the 988 steel buildings damaged because of the earthquake and referenced by the literature 6), 80 percent of these have less than 5 stories. Almost all buildings, that completely collapsed, had 2~5 stories, and any high buildings, which had more than 7 stories, did not collapse.

Among different damaged parts, the beam-column welded connections and column-column welded connections suffered the most. These damage of welded joints are described in next chapter.

Apart from welded joints, the following damage were observed.

(a) Local buckling behaviors in end parts of square section columns and typical column-yield type failures due to these behaviors.

(b) Fractures, which were along the axis of a member, in corner part of square section columns (**Fig.8**). These were observed in columns suffering from fire after the earthquake.

(c) Brittle fractures in the base metal of square section columns, just above the floor, in slender building (so called "pencil buildings") (**Fig.9**).

(d) Flexural buckling and fractures due to local buckling in the base of square section columns on first floors (**Fig.10**).

(e) Flexural buckling and fractures of bracing. The buildings generally leaned after these damage.

(f) Fractures of anchor-bolts on exposed-type column bases.

(g) Shear failure of encased and lower concrete on column bases.

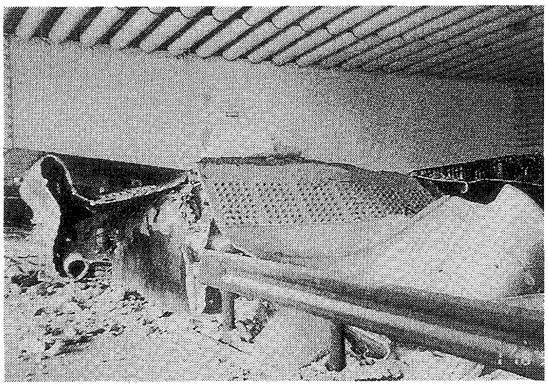

Fig.4 Collapse of steel pier.[6)]

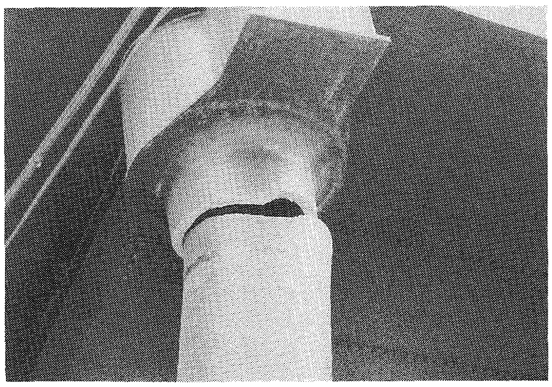

Fig.6 Brittle fracture of circular pier made by centrifugal casting.

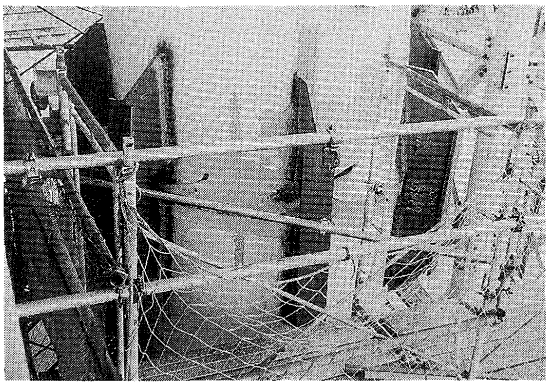

Fig.5 Crack due to local buckling.[6)]

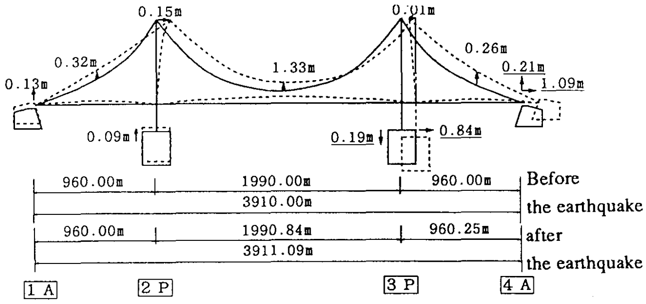

Fig.7 The relative displacement of "Akashi-Kaikyo Bridge".[9)]

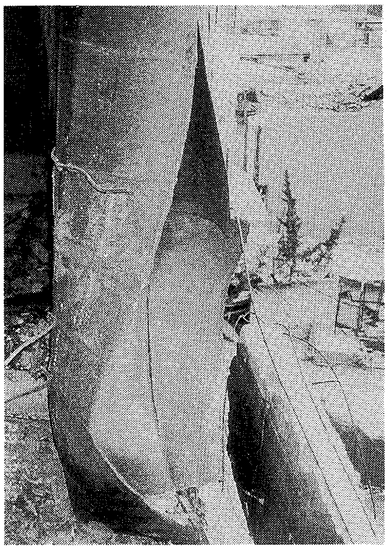

Fig.8 Fracture in corner part of square section column.[6)]

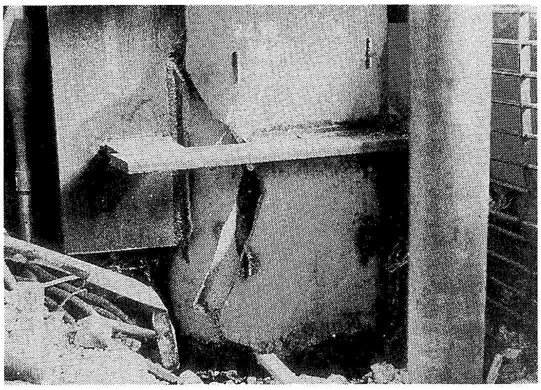

Fig.9 Brittle fracture in base metal of square section column.[6)]

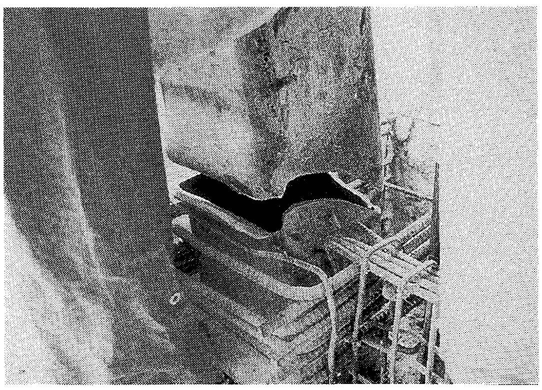

Fig.10 Flexural buckling and fracture due to local buckling in base of square section column.[6)]

4. Damage in welded joints of steel buildings

4.1. An outline of damage [1),6),12)]

As compared with steel viaducts and bridges, a lot of damage was reported in welded joints of steel building

Fig.11 Crack and fracture probably caused by insufficiency of strength.[6)]

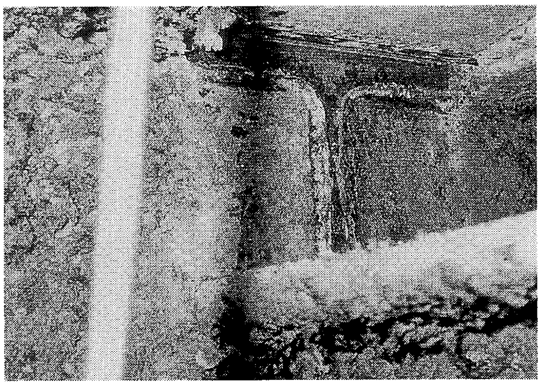

Fig.12 Fracture probably caused by insufficiency of strength.[6)]

frames.

In the steel building, the beam-column connections are usually made by welding. These parts have the largest load, so that they become the most important parts in the frame. Half of the damage in steel buildings were fractures in the beam-column connections, and these are divided two groups, damage caused by insufficiency of strength and by brittle fractures. Apart from these damage, fractures of welded joints in column-base connections, in beam-bracing connections and in connections of space trusses, were also reported.

4.2. Insufficiency of strength [1),6),12)]

Cracks and fractures, probably caused by insufficiency of strength in the welded joint, were observed in the following locations (**Fig.11,12**).

(a) In fillet weld joints, which had smaller sizes of throat depth than usual.

(b) In old-type joints, in which discontinuous parts were not designed with enough care.

(c) At short bead-lines in joints of small additions, which were not controlled carefully.

These were found in comparatively old buildings and were destroyed without residual deformation of the members. Most of these buildings hardly showed the energy absorption expected for steel structures, and were seriously damaged, or collapsed. As a result, quality control will become a serious problem for new buildings constructed in the future. A major problem is how to repair these low-strength buildings, of which these are still many in Japan.

4.3. Brittle fracture [1),6),12)]

Brittle fractures were observed in beam-column connections, which were welded according to the present design standard. As **Fig.13** shows diagramatically, typical modes of fractures are divided as follows.

(a) Brittle fractures in beam-flanges, started from the toe of the scallop in the web.(**Fig.14**).

(b) Brittle fractures at heat-affected zones in the beam-flange or the diaphragm, started from the backing strip or the end tab (**Fig.15**).

(c) Brittle fractures at heat-affected zones or base metal of the diaphragm in the column-diaphragm connections (**Fig.16,17**).

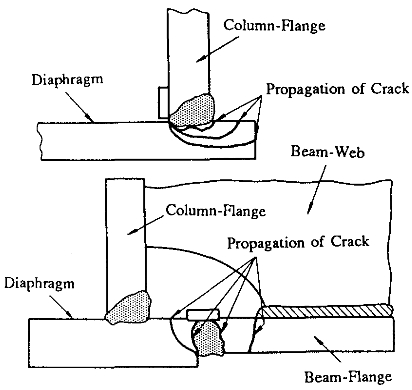

Fig.13 Typical modes of fracture at the beam-column connection in the Kobe earthquake.[1)]

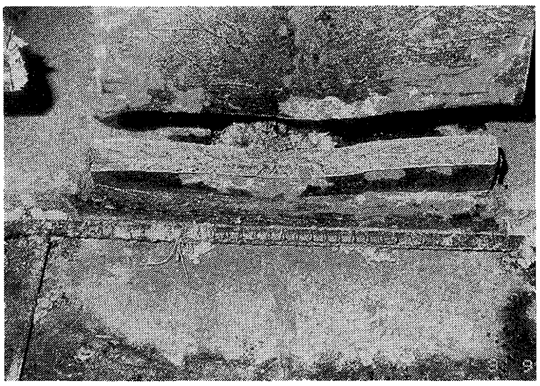

Fig.14 Brittle fracture in beam-flange.[6)]

It is ascertained by marks of local buckling, peeling of paint or mill scale and Luders's lines, that these fractured after large plastic deformation. In this observation, these are regarded as "the general yield brittle fracture", because these fractured at stress concentration points or discontinuous points of shape after absorption of seismic energy. As the fracture was may be caused by the hardness of metal, so it differ from "the low stress brittle fracture", which hardly absorbed seismic energy.

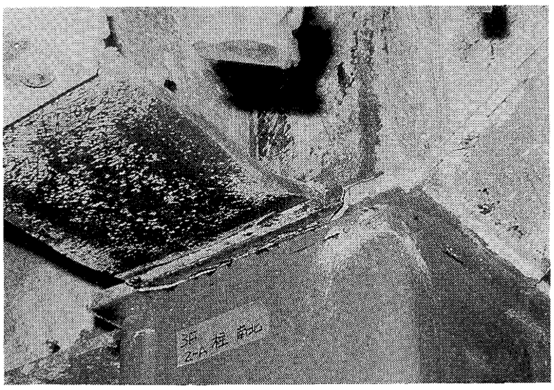

Fig.15 Brittle fracture at heat-affected zone in beam-diaphragm connection.[6)]

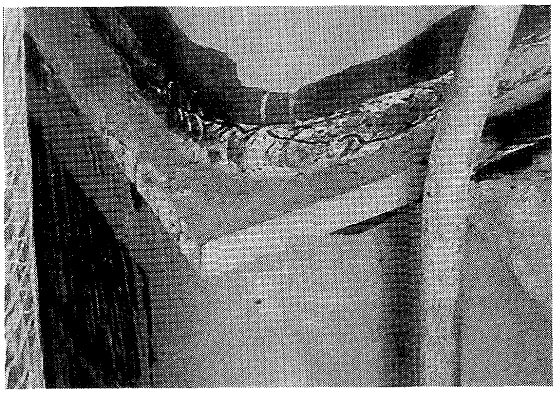

Fig.16 Crack at heat-affected zone of diaphragm in column-diaphragm connection.[6)]

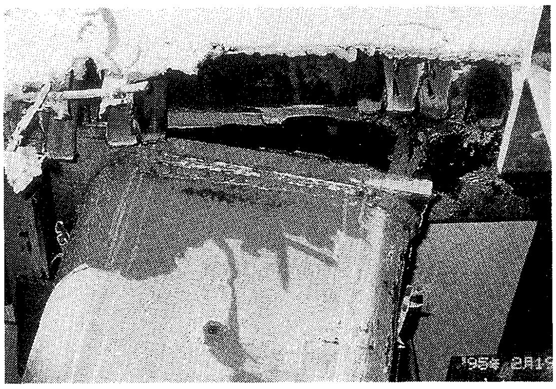

Fig.17 Fracture at base metal in column-diaphragm connection.[6)]

Moreover 57 instances of brittle fracture, without marks of plastic deformation at all, were found in chord members of mega-structures, composed of rigid truss types of built-up chord, lateral and diagonal members. Damaged members had box sections, built of a couple of channel-shaped steels (maximum thickness in over 50cm) by submerged welding. Fractures were observed at the following locations.

(a) The upper points at a distance of 30~50cm from chord-chord welding connections (**Fig.18**). This type was found at 13 locations.

(b) The points at which chord member, lateral member and diagonal member are connected by welding (**Fig.19**). This type was found at 7 locations.

(c) In the chord-chord welding connections (**Fig.20**). This type was found at 37 locations.

It seems that (a) have no relations with welding, because these were fractured in the base metal. But the possibilities are pointed that the fillet welding of erection pieces and other additions become starting points for fractures.

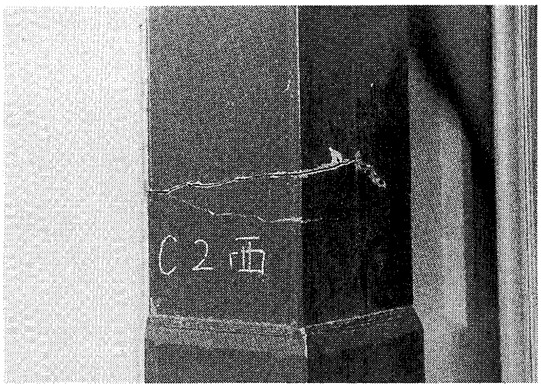

Fig.18 Fracture of base metal in chord member of maga-structure.[6]

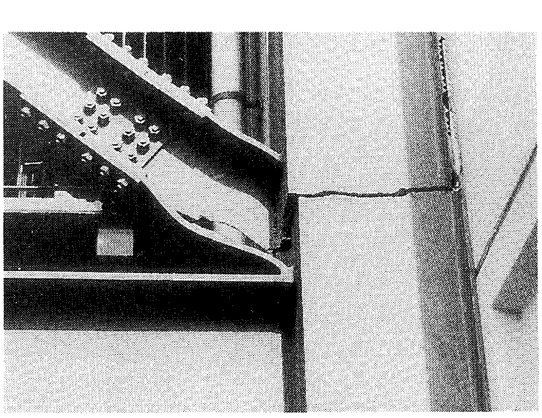

Fig.19 Fracture at welded connection of chord-lateral-diagonal members on maga-structure[6]

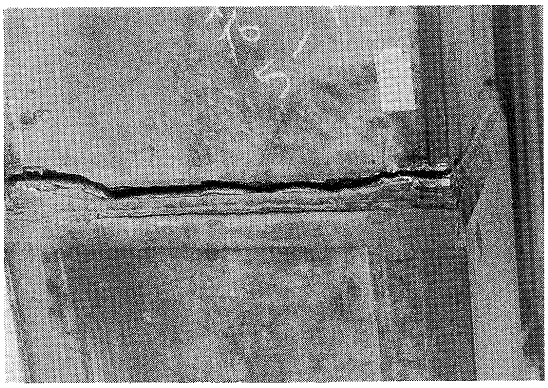

Fig.20 Fracture at the welded connection of chord-cord member of maga-structure[6]

Damage mentioned in this section occurred in welded joints according to the recent design standard and execution methods. Therefore, more studies must be made about the cause of fractures and about energy absorption capacity required for these structures.

4.4. Comparisons with the Northridge Earthquake [12),13),14)]

The Northridge Earthquake (magnitude of 6.8), which struck the Los Angeles area on January 17, 1994, just the same day one year before the Kobe Earthquake occurred, was an impulse type of epicentral earthquake, too. Also in the Northridge, brittle fractures were observed in many of the beam-column connections of steel buildings (**Fig.21**), called "Steel Moment Resisting Frame (SMRF)". **Fig.22** shows the typical mode of cracking in the Northridge incident. But these fractures are differ from those in the Kobe.

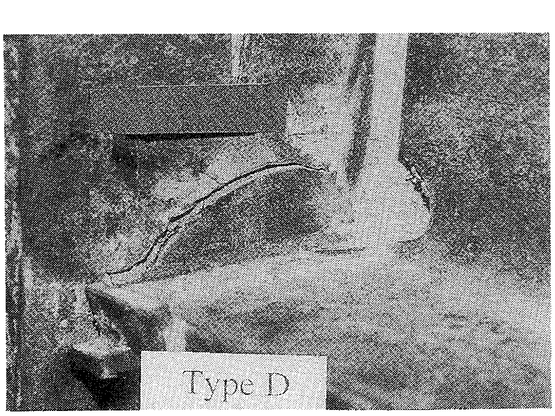

Fig.21 Brittle Fracture in beam-column connection due to the Northridge Earthquake.[12]

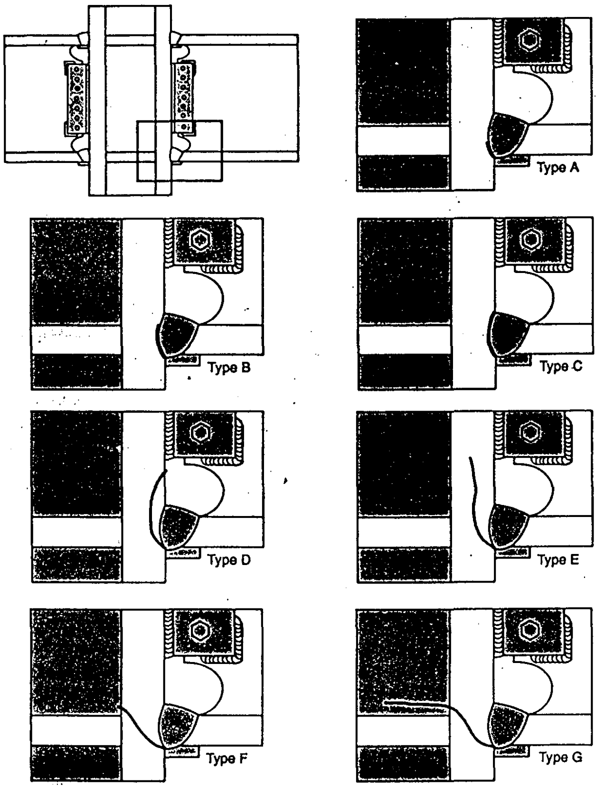

Fig.22 Typical modes of crack due to the Northridge Earthquake.[14)]

In the Northridge, these connections were fractured without absorption of seismic energy by plastic deformation, against those in Kobe which were fractured with them, except mega-structures as mentioned above.

Differences of beam-column connections between Japan and USA are listed as follows.

(a) Difference of the steel and the welding material.

(b) Difference between the shop welding (Japan) and the field welding (USA).

(c) Difference in numbers of rigid joints. In USA only minimum numbers of connections are jointed rigidly, against all connections jointed rigidly in Japan. In USA sections of members, composed rigid joints, are larger than in Japan.

(d) Difference of design seismic load and of limited deformation.

But the reports about welded joints in Kobe are fewer than those about the Northridge. So, it dose not appear in damage investigations presented by now that the Northridge-type of brittle fracture did not occur at all in Kobe.

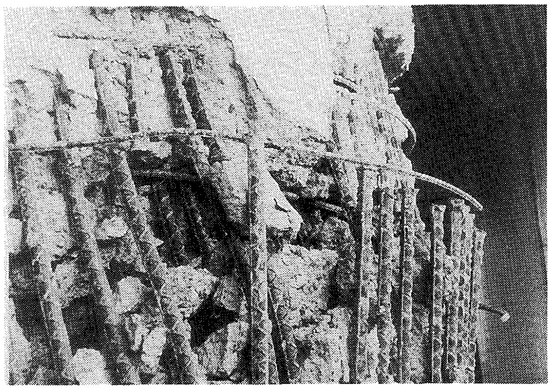

Fig.23 Damage of "the gas pressure welding connection".

5. Closing remarks

The above is an outline of damage to steel structures, especially damage at welded joints, due to The Kobe Earthquake, given in investigations and articles.

In this research damage, that was reported from experimental studies before the earthquake and various types of new damage, were found among steel structures. Some studies have been made about such damage, but detailed studies and considerations will be presented gradually in the future.

Beyond the scope of this review, "gas pressure welding connections", the most popular method for joining reinforcing bars, also incurred heavy damage. The causes of these failures have also been studied **(Fig.23)**.

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[3-3] J.P.Barded, F.Oka, M.Sugio and A.Yamashita, "THE GREAT EARTHQUAKE DISASTER Preliminary Report.", 1995.2, 71p, (in English)

[3-4] Disaster Prevention Research Institute , Kyoto University, "Preliminary Report on the Great Hanshin Earthquake of January 17 ,1995 (DPRI News Letter).", 1995.2, 48p, (in English)

[3-5] EERI (Earthquake Engineering Research Institute), "The Hyogo-Ken Nanbu Earthquake.", 1995.3, 116p, (in English)

[3-6] Risk Management Solutions ,Inc. and Failure Analysis, Inc., "Japan The Great Hanshin Earthquake.", 1995.1, 35p, (in English)

[3-7] EQE International, "The January 17, 1995 Kobe Earthquake an EQE Summary Report."

[3-8] M.Okubo, "Preliminary Report on the Hyogoken-Nanbu Earthquake, Japan, of January 17,.", 1995.2

4. Information about the earthquake in "Internet "

(Indexes about the earthquake disaster --these are some of them)

[4-1] http// www. kobe-cufs. ac. jp/ kobe-city/ disaster/ index. html --- (in English and Japanese)

[4-2] http// www. iij. ad. jp/ earthquake --- (in English and Japanese)

[4-3] http// www. kanagawa-u. ac. jp/ earthquake --- (in English and Japanese)

[4-4] http// www. ntt. jp/ quake/ eqc --- (in English and Japanese)

[4-5] http// www. csl. sony. co. jp/ earthquake --- (in English and Japanese)

[4-6] http// www. cul. go. jp/ earthquake/ akashi. html --- (in English and Japanese)

[4-7] http// www. darkwong. uoregon. edu/ rukat/ info/ quake. html --- (in English)

(graphical reports)

[4-8] http// www. gsi-mc. go. jp/ jis/ kobe/ photo --- (in English and Japanese)

[4-9] http// itcw3. aist-nara. ac. jp/ earthquake/ imafes --- (in English and Japanese)

[4-10] http// hdsn. eoc. masda. go. jp/ quide/ kobe. html --- (in English and Japanese)