STUDY ON INSPECTION AND EVALUATION OF DAMAGED STEEL STRUCTURE IN THAILAND

BY

WARAKORN TANTRAPONGSATON

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING AND TECHNOLOGY)

SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY

THAMMASAT UNIVERSITY

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A Thesis Presented

By

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Abstract

STUDY ON INSPECTION AND EVALUATION OF DAMAGED STEEL STRUCTURE IN THAILAND

by

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This research emphasized on indicating the damage that occurred on different existing steel structures, and identifying the causes of damage, by using the methods of visual inspection and evaluation. In addition, the interviews of the maintenance personnel who directly involved with the maintenance works were performed in order to acknowledge the countermeasures to handle the damage. The target steel structure consists of steel buildings, steel highway bridge, steel power plants, and steel billboards.

The results indicated that the majority of damage or defect on steel structures was divided into two types; 1) the damage during construction process, 2) the damage after construction. For the first type of damage, i.e. the damage during the construction process of the structure are the damage on the steel welding, and the defect of painting caused by poor workmanship of the steel work. From the results of visual inspection and evaluation of the target structure, it is found that types of the defects of welding are undercut and porosity, which assessed as “Unacceptable” accordion to the standard of Department of Public Works and Town & Country Palnning, DPT 1561-51. This might decrease the strength of the welds. Also, the painting defect mostly occurred on the inaccessible parts of the steel, and this defect might leads to severe corrosion damage.

For the second type of damage, i.e. the damage after construction or that occurred during the service life of the steel structures, the damage due to corrosion occurred when the painting deteriorated. This severity of damage was controlled by two factors, which are the surrounding environmental condition, and the quality of maintenance work. The result of visual inspection and evaluation showed that the structure located in sensitive area to corrosion has more severity level of damage than the normal area, and structure that has better maintenance work tends to have less severity level of damage.

The countermeasure to solve and prevent the damage proposed in this research was divided into two approaches, maintenance approach, and construction approach. For the first approach, a standard or guideline for the inspection and maintenance of the steel structure in Thailand should be drafted. For the second approach, the followings should be drafted or established; 1) material specification to control the quality of the steel product from the different manufacturers (domestic and foreign factories), 2) construction handbook for the durable steel structure, 3) the system for accrediting structural steel fabricator.

Keywords: Steel Structures, Inspection, Evaluation, Damage, Corrosion, Defects, Deterioration.

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Chapter 1
Introduction

1.1 General Background

Durability of a structure after constructed is an important issue to be consider by an engineer who desired long-lasting service life of the structures. So, good maintenance system is highly essential to maintain durability of a structure.

As a material for the main structure, steel is known to be used for truss structure, but steel also had been used widely in Thailand as a material for a construction industry, particularly railway bridges, highway bridges, billboards, power plants and buildings. The most common ways to maintenance the steel structure is to replace the steel section (load-carrying members) after 30% or more of the steel sectional area has been lost by corrosion or when the section deformed.

To acknowledge the condition of a steel structure, a structural inspection and evaluation shall be performed periodically by a specialized inspector. The inspections results will be evaluate and analyze for the cause of damage, then the maintenance crew will plan the action to solve the problem.

It's important to keep monitoring a steel structure to prevent the structural failure, either by damage from deterioration during service life, or damage from defect during construction process, or both type of damage.

1.2 Statement of Problem

Nowadays, there are a lot of damaged steel structures in Thailand. The damage might cause from the defect during construction process or the deterioration during service life. Additionally, defect during construction might cause by poor workmanship and poor construction work, and deterioration during service life might cause by the surrounding environment and poor quality of maintenance work. Also, both type of damage might result in decreasing of the structural capacity, and might cause a structural failure in the future. Finally, without a proper inspection and maintenance of steel structure, the service life of a steel structure might decrease significantly to where maintenance and repairing is no longer to be worth applying.

Another factor that can accelerate the deterioration of the steel is the quality of the steel material; i.e. poor material might deteriorate faster than the normal material. Furthermore, nowadays many steel products or steel materials were imported from the foreign countries which might not be as good as that were manufactured in Thailand; i.e. the steel material that were imported from China was found to be poor by many contractors and domestic fabricators.

Lastly, the problem from poor construction work was found commonly throughout Thailand, since there is no to accreditation system to control the fabricators and welders. This leads to poor construction works, and this might develop into severe damage to the structure, and sudden structural failure.

1.3 Objective of Study

This research mainly focuses on indicating the damage and defect that occurred to the steel structure, identify the cause of the damage, and propose the countermeasure to solve and prevent the damage. The objective of this research can be listed as follow:

1. To inspect and evaluate the damaged steel structure based on the existing standards.
2. To interview the maintenance personnel about the maintenance work on a certain structure.
3. To indicate the damage and defect occurred to the steel structure.
4. To identify the cause of damage and defect that occurred on the steel structure.
5. To propose countermeasures to solve and prevent the damage that occurred on the steel structure.

1.4 Scope of Study

This research was mainly focused on inspecting the damaged structure in Thailand, which are constructed by using steel structure as their main structure. And interview the maintenance personnel of those structures. The scope of this thesis was subject to the following lists:

1. The target steel structures were located on different regions in Thailand, and the types of the structure are consisting of steel highway bridges, billboards, power plants, and buildings.
2. The inspection was conducted by only visual inspection method on weld connection, bolt connection, and steel coating to prevent any impact to the structural appearance or properties, and to avoid any disturbance to the personnel within those structures.
3. The inspection was conducted only on the main structure members and connections
4. The identity of the steel structure that was inspected will not be disclosed to prevent any reputation issue.
5. The interview was conduct to the maintenance personnel and the engineer who responds for that certain structure.

Chapter 2
Literature Review

2.1 Steel Structure Damage and Defect

2.1.1 Corrosion Damage

Mars G. Fontana (1987) revealed that corrosion is the deterioration of a material because of the reaction with an environment which can be classified into "Wet corrosion" and "Dry corrosion". Wet corrosion occurs when liquid is involved (usually aqueous solution or electrolytes), like the corrosion of steel by water. Dry corrosion occurs by the corrodents in vapor or gas phase and most often associated with high temperatures, like the attack on steel by furnace gases. Also even small amounts of moisture can highly affect the severity of the corrosion, like when moist chlorine or chlorine dissolved in water is extremely corrosive comparing to dry chlorine which is noncorrosive to steel.

In general, corrosion damage is known as the decreasing of steel section thickness. The corrosion damage can affect the maintenance cost of the structure, changing the material to more resistance to its condition can save the maintenance cost by a good amount, also many power plant are shutdown or stopped because of the unexpected corrosion failure. Corrosion monitoring or inspection is helpful to prevent the corrosion failure in steel structure.

2.1.2 Welding Defects, Causes, and Correction

Baughurst et al. (2009) revealed that welding defects can affect the performance of the weld greatly and even the inconspicuous weld defect could turn structure to be inefficient for its purpose. Weld defects refer to the imperfection of weld characteristics. The defects which involve with the geometric imperfection of the weld, such as the protrusion of weld metal over the toe or root of the weld called "Overlap" (Fig 2.1), Concavity and Convexity of the weldment (Fig 2.2) are caused by poor welding techniques or incorrect welding condition such as current too low, insufficient preheating, welding speed too fast, incorrect edge preparation, and short arc length, which can be repaired by either grinning of the excess weld, or by filling with further weld material for the correct size of weld.

But there are more severe type of defects which can highly affect the capacity of the weld such as Cracking of weld, Undercutting of weld (Fig 2.1) which is an unfilled groove along the edge of the weld, and Porosity on the weldment (Fig 2.3) which cause by weld cooling problem for Cracking, and cause by poor workmanship for Undercut and Porosity. Crack and Porosity can be repaired by grinning/gouging out the defective area and re-welding, and Undercut can be repaired by welding up the resultant groove with the smaller electrode.

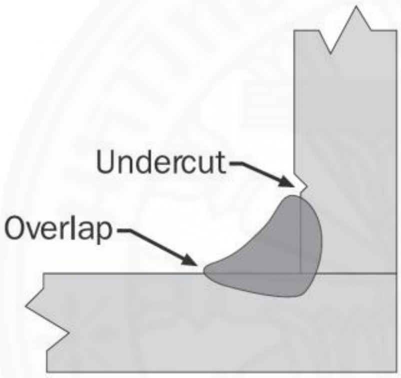


Fig 2.1 Undercut and Overlap welds (Baughurst et al, 2009)

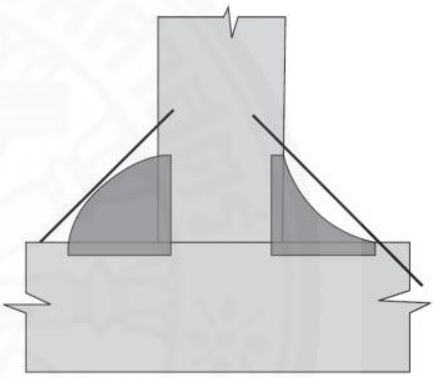


Fig 2.2 Convex and Concave welds (Baughurst et al, 2009)

Fig 2.3 Porosity (Baughurst et al, 2009)

2.2 Thailand Steel Inspection and Evaluation Standards

In Thailand there aren't many standards that are supported the use of steel for structural purposes, making the structural steel inspection to be overlooked in most of small-scale steel structure construction and maintenance, only in large-scale structure to see steel inspection and maintenance as an important task.

"Structural Steel welding inspection standard using Non-destructive testing" is the standard that was published by the "Department of Public Works and Town & Country Planning" for the purpose to inspect the steel weld connection. The standard was divided into five sub-standards follow, as each sub-standard represents different Non-destructive inspection method for welding shown below;

- DPT 1561-51: Standard Method for Weldment Examination in Steel Structure using Visual inspection Method
- DPT 1562-51: Standard Method for Weldment Examination in Steel Structure using Ultrasonic Testing Method
- DPT 1563-51: Standard for Weldment Examination in Steel Structure using Magnetic Particle Testing Method
- DPT 1564-51: Standard for Weldment Examination in Steel Structure using Penetrant Testing Method
- DPT 1565-51: Standard for Weldment Examination in Steel Structure using Radiographic Testing Method

Each method has specific acceptance criteria to tell if the structure or a part of structure is acceptable or not.

2.2.1 Welding Visual Inspection Acceptance Criteria

DPT 1561-51 specified the acceptance criteria for welding visual inspection in total of twelve criteria, to check the weldment according to the type of defect such as crack, undercut, undersize weld, porosity, and convexity, etc. Welding visual inspection acceptance criteria show in Table 2.1.

Table 2.1 Welding Visual Inspection Acceptance Criteria (DPT 1561-51)

No.	Type of defect	Descriptions	Acceptance criteria
1.	Crack	All kind of cracks	Unacceptable
2.	Porosity	2.1. Statically-loaded welds with non-Tubular connections	
		a. Butt Joint, groove weld, Full Penetration weld.	Unacceptable
		b. Fillet weld and other weld (excluding a.)	Diameter summation of piping porosity which has > 1mm diameter shall not exceed (1) 10mm in each 25mm of weld length and (2) 20mm in each 300mm of weld length.
		2.2. Cyclically-loaded welds with non-Tubular connections	
		a. Butt Joint, groove weld, Full Penetration weld.	Unacceptable
		b. Fillet Welds and Other weld (excluding a.)	The frequency of piping porosity in fillet welds shall not exceed one in each 100mm of weld length and the maximum diameter shall not exceed 2.5mm
		c. Fillet Welds on Stiffener and Wed	Diameter summation of piping porosity shall not exceed (1) 10mm in each 25mm of weld length and (2) 20mm in each 300mm of weld length.
3.	Crater Cross Section	Intermittent Fillet Weld	All craters shall be filled to provide the specified weld size, except for the end of intermittent fillet welds outside of their effective length

Table 2.1 Welding Visual Inspection Acceptance Criteria (DPT 1561-51) (Continue)

No.	Type of defect	Descriptions	Acceptance criteria
4.	Undercut	4.1. Statically-loaded welds	
		a. For material less than 25mm thick	(1) Undercut shall not exceed 1mm, with the following exception: (2) undercut shall not exceed 2mm for any accumulate length up to 50mm in any 300mm
		b. For material equal to or greater than 25mm thick	Undercut shall not exceed 2mm for any length of weld
		4.2. Cyclically-loaded welds and Tubular welds(All loads)	
		a. Primary members	Undercut shall be no more than 0.25mm deep when the weld is transverse to tensile stress.
		b. Under any design loading condition (excluding a.)	Undercut shall be no more than 1mm deep for all other cases
5.	Undersized Weld	5.1. All types of welds	The undersize portion of the weld shall not exceed 10% of the weld length.
		5.2. Web-to-flange welds on girders (fillet welds)	Under run shall be prohibited at the end for a length equal to twice of the flange.
6.	Convexity	Fillet Welds (Sort by Width of Weld [W])	
		a. W <= 8mm	Convexity shall not exceed 2mm
		b. 8 < W < 25mm	Convexity shall not exceed 3mm
		c. W >= 25mm	Convexity shall not exceed 5mm

Table 2.1 Welding Visual Inspection Acceptance Criteria (DPT 1561-51) (Continue)

No.	Type of defect	Descriptions	Acceptance criteria
7.	Overlap	Fillet Welds, Butt Joint	Unacceptable
8.	Incomplete Fusion	Fillet Welds	Unacceptable
9.	Reinforcement	Reinforcement equal thickness, and different thickness	High of Reinforcement shall not exceed 3mm
10.	Underfill	Butt Joint, groove weld, Full Penetration weld.	Unacceptable
11.	Flush Surface	Butt Joint, groove weld, Full Penetration weld.	
		a. Thickness of welds and Steel part after Grinding	Shall not below than 5% of the thinnest steel part's thickness and not exceed 1mm
		b. High of Reinforcement	Shall not exceed 1mm except the surface level of the weld has to be the same as the steel part.
12.	Flush Finishing	The Work part need to surfacing and grinding, The roughness of the surface mush not exceed 6.3 micron and grinding mush be in specific directions as follow	
		a. Grinding parallel with a Primary stress	Roughness shall be in the interval of 3.2 to 6.3 micron
		b. Grinding in any direction	Roughness shell not exceed 3.22 micron

2.3 Steel Structure Inspection and Evaluation

2.3.1 Welding inspection

AWS D1.1/D1.1M (2010) state that all welds shall be visually inspected and shall be acceptable based on the criteria specified in Appendix A. The welding visual inspection criteria is consist of eight discontinuity category and inspection criteria such as (1) Crack Prohibition, (2) Weld/Base-Metal Fusion, (3) Crater Cross Section, (4) Weld Profiles, (5) Time of Inspection, (6) Undersize Welds, (7) Undercut, (8) Porosity. The applicability of each criterion depends on the loading condition and type of connection (Tubular connection or non-tubular connection) of the welds. Usually welds will be inspected after weld process to check the welds is in the acceptable range of welding inspection criteria or not, the welds that does not satisfied the criteria shall be rejected or corrected.

2.3.2 Bolt inspection

JASS 6 state that, for bolt fastening, after finish tightening process the bolt connection shall be inspected, to check the quality, size, locking device, and tightness level of the bolt. The tightening check can be simply done by using torque wrench. Over-tightened bolt shall be replaced, and loose bolt shall be tightened correctly.

JIS B 1186 state that, for high strength hexagon bolt, nut, and washers shall be inspected to ensure the properties of the bolt connection such as, Shape and dimension using direct measurement, appearance of the bolt such as the surface defect test using liquid penetrant testing or magnetic particle testing to indicate the crack. Also, the mechanical properties of the bolt shall be tested using bolt test pieces as a sample of bolt, nut, and washer.

RCSC state that the instructions for the inspector to inspect the bolt connection for a steel structure after assembled, the instruction divided in to three parts depend on the type of joints, whether it’s a snug-tightened joint, pretensioned joint, or slip-critical joint. The instruction for snug-tightened joint was to inspect visually to ensure contact of the element pile is firm, washer has been used, and all of the bolts in the joint were tightened sufficiently as specified in the RCSC requirements. Furthermore, for pretensioned joint was to visual inspection after pretensioned is permitted in lieu of routine observation. Finally for slip-critical joint, it stated that the joint shall be visually verified the faying surface of slip-critical joint whether it meets the specification or not.

2.3.3 Paint Defect and Damage

ISO 4628-1 state the general designation system for paint and varnishes evaluation of degradation of coating based on quantity and size of defects and the intensity of change by means of ratings on a numerical scale ranging from 0 to 5, while “0” means “No defects”, and “5” means “Very severe”. The rest of the rating (1, 2, 3, 4) corresponds the severity range from low severity to high severity accordingly. Paint shall be inspection visually to indicate the defects and its severity level.

ISO 4628-2 to ISO 4628-5 specified the assessment of degree of blistering, rusting, cracking, flaking of paint accordingly, based on the designation system state in ISO 4628-1. Photographic reference is given for each defect type based on quantity and size of defect, as shown in Appendix B.

TIS 2387-2555 state the requirements about the durability of the corrosion firmer such as Flexure durability, Abrasion durability, Durability under constantly condenses moisture and salt spray resistance. Additionally, in durability under moisture section, it specified the designation for degree of blistering and degree of rusting using photographic reference method following ASRM 714 standard, similarly to what specified in ISO 4628.

2.4 Construction and Fabrication Guidelines

AISC 360-10 state the guideline for construction and fabrication in many interesting topic such as, welded construction, bolted construction, shop painting, and erection of steel structures. Firstly, an overall of the guideline state the requirement of the construction work starts from welded construction which required the technique of welding, the workmanship, appearance, and quality of welds to followed AWS D1.1/D1.1M standards. Furthermore, the requirement for bolted construction was overall about the assembly process and fabrication process followed RCSC Specification for structural Joints Using High-Strength bolts. Secondly, an overall of the shop painting guide was including the requirement of the paint on different condition of the steel section, such as inaccessible surfaces, contact surface, finish surface, surface adjacent of field welds. In addition, the requirement mainly emphasized on surface cleaning and painted prior assembly, the faying surfaces (contact surfaces) should blast cleaned and subsequently coated with coating specified in RCSC Section 3.2.2(b). Also, the finished surfaces shall be protected against corrosion by corrosive coating that can be removed before erection. Finally, the erection section stated the simple requirement for field welding that the surface near the welding area shall be prepared to assure the quality of the welds.

2.5 Quality control

2.5.1 Material Specification

BC1: 2012 state the quality control of steel product in term of the steel adequacy assessment method, this method evaluate the steel specific properties based on two criteria, which are (1) By certification and (2) By Material Testing. Further, this method of evaluation of assessment will classified the steel material in to three classes. Class 1 steel material, this means that the steel assets within this class are certified material manufactured with approved quality assurance. Class 2 steel materials, this means that the steel assets within this class are non-certified material which meet the material performance requirements through material testing, and manufactured with approved quality assurance. Class 3 steel materials, this means that the steel assets within this class are steel materials which do not meet at least one of the two requirements material performance requirements and quality assurance requirements.

The objective of this method is to control the quality of steel material that under-spec based on BS 5950 and Eurocode 3, by adding a strength reduction factor in the design to decrease the design strength of the steel product. Additionally, different design factor for each class of the steel material was specified in BC1 as well as the design parameters. Furthermore, design factor could decrease the strength of the steel material to only 90% of the real capacity.

2.5.2 Structural steel fabricators accreditation

Structural steel fabrication accreditation scheme by *Singapore Structural Steel Society* state the accreditation for the fabricator with the objectives of to raise the standard of steel fabricators serving the construction industry. The accreditation scheme grades the steel fabricators according to their capabilities, based on their track records, financial status, technical capability and the standard of the fabrication plants. Accreditation Scheme will ensure that the structural steelwork construction is carried out by suitably qualified fabricators.

Chapter 3
Methodology

To indicating the damage and defect that occurred to steel structure, and to identify the cause of the damage, Real site inspection and interview of maintenance personnel are necessary to obtain enough information that leads to the countermeasure to solve and prevent the damage. The target structures were Steel highway bridges, steel billboards, steel power plants, and steel buildings.

3.1 Maintenance Personnel Interview

A good way to obtain the information about the current situation, problem, and maintenance criteria of the damaged steel structures is to interview the maintenance personnel of those structures. This approach strongly helps on identify the indirect cause and root cause of the damage and defect for steel structure in Thailand.

There are no specific question that were asked in the interview, the interview were carried out as a conversation on a topic or issues about the maintenance work, damage occurred on the structures, the background of the structure, and the opinion or the thought on a topic such as Thailand standards and guide line, construction system in Thailand, and steel structure construction in Thailand. These questions were asked to ascertain the current situation of the steel structures was damaged, and to ascertain the encounter measure used to response those damages. And to obtain some ideas about how to improve the steel structure maintenance, standards and guideline, steel structure construction system in Thailand.

3.2 Inspection and Evaluation on Steel Structure

Visiting the real construction site or the real structure is the best way to acknowledge the damage and defect that occurred to the steel structure under different environments, locations, and different functions.

Site inspections were mostly carryout by using Visual inspection (VT), since this method does not affect property, appearance, or function of the structures.

The flow chart shown in Fig 3.1 indicates the visual inspection routine used in this research, the visual inspection and evaluation was divided in to two target areas which are steel connection inspection and steel surface inspection. The steel connection inspection was focused on both weld connection and bolted connection based on DPT 1561-51 and JASS 6 accordingly. Steel surface inspection was focused on paint inspection and corrosion on the steel surface based on TIS 2387-2555 and ISO 4628 for both damage.

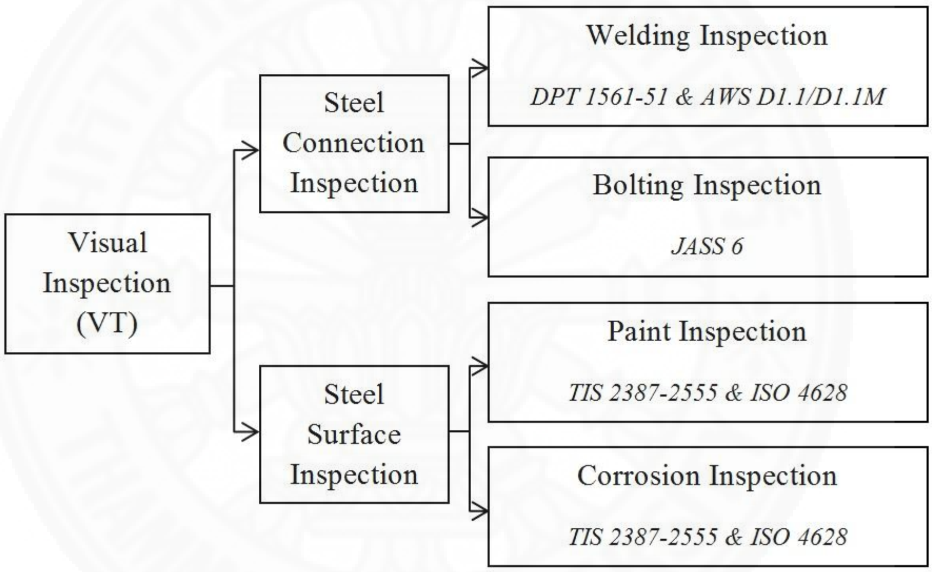


Fig 3.1 Visual Inspection Flow Chart

The inspection data were recorded in the form of table and photo for each steel structure that was visited, and those structures were evaluated based on the standards to indicate the level of damage and state of the structure.

3.2.1 Welding Inspection and Evaluation criteria, and Equipment

3.2.1.1 Welding inspection and evaluation criteria

In this research, visual inspection method was used to inspect the steel structure with welded connections. There are 3 criteria used listed below:

1. Crack inspection
2. Porosity inspection
3. Undercut inspection

These criteria was selected from criteria in the DPT 1561-51, which was considered to be the most severe welding defects that could cause dramatic decrease of the capacity of the steel structure. The welding inspection criteria are similar to the criteria in DPT 1561-51 as shown in Table 3.1.

Table 3.1 Welding Visual Inspection Acceptance Criteria

No.	Type of defect	Descriptions	Acceptance criteria
1.	Cracking	All kind of cracks	Unacceptable
2.	Porosity	a. Butt Joint, groove weld, Full Penetration weld	Unacceptable
		b. Fillet weld and other weld (excluding a.)	Diameter summation of porosity which has > 1mm diameter shall not exceed (1) 10mm in each 25mm of weld length and (2) 20mm in each 300mm of weld length.
3.	Undercut	a. For material less than 25mm thick	(1) Undercut shall not exceed 1mm,
		b. For material equal to or greater than 25mm thick	Undercut shall not exceed 2mm for any length of weld

3.2.1.2 Welding inspection equipment

The equipment used in welding inspection was listed as follow:

1. Ruler
2. Taper Gauge (Shown in Fig 3.2)
3. Tape measurement
4. Welding Gauge (Shown in Fig 3.3)
5. Magnifier
6. Ladder

Fig 3.2 Taper Gauge

Fig 3.3 Welding Gauge

3.2.2 Bolting inspection criteria

3.2.2.1 Bolting inspection criteria

According to the regulation stated in JASS 6 that fastener inspection for every bolt after tightening is necessary. But since this research is targeted the existing steel structure makes difficulty on getting those certain structure design data or drawing, so it impossible to follow the criteria stated in JASS 6 directly.

Bolting inspection criteria used in this research was to check the appearance of the bolt connection on the existing steel structure. The criteria were to visually check the damage on the bolt connection such as bolt connection surface damage, bolt connection deformation, and bolt connection failure.

3.2.3 Steel coating inspection criteria and equipment

3.2.3.1 Steel coating inspection criteria

The inspection criteria for steel coating or anti-corrosive paint used in this research was followed the international standard ISO 4628. The inspection carried out by using visual inspection method on the steel surface and photographic reference method (shown in Appendix B), and then recorded the inspection data in the form of photograph and table. The data was evaluated based on the quantity, size, and intensity of change of each defect and damage according to ISO 4628.

The anti-corrosive paint damage was evaluated by using the criteria shown in Table 3.2 to Table 3.9 for each type of defect, and comparing with the reference photo in Appendix B. The procedure of steel anti-corrosive evaluation is showing in Fig 3.4 below. The final evaluation results were the rating or severity level for each damaged area.

3.2.3.2 Steel coating inspection equipment

The equipment used in steel coating inspection was listed as follow:

1. Ruler
2. Tape measurement
3. Camera
4. Reference photo (from ISO 4628)

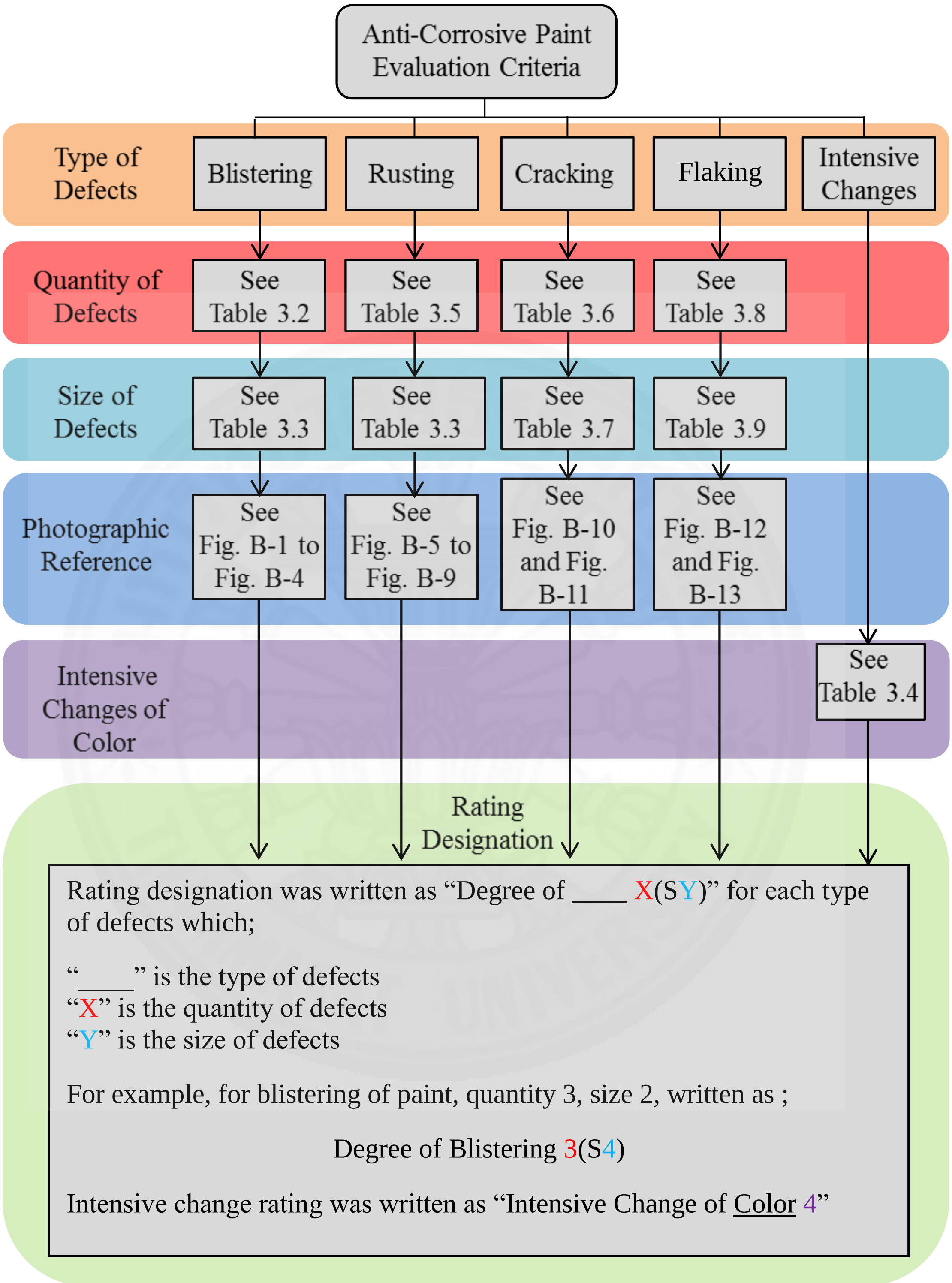


Fig 3.4 Anti-Corrosive paint evaluation criteria

Table 3.2 Rating scheme for designating the quantity of defects (ISO 4628-1)

Rating	Quantity of defect
0	none, i.e. no detectable defects
1	very few, i.e. small, barely significant number of defects
2	few, i.e. small but significant number of defects
3	moderate number of defects
4	considerable number of defects
5	dense pattern of defects

Table 3.3 Rating scheme for designating the size of defects (ISO 4628-1)

Rating	Size of defect [a]
0	not visible under x magnification
1	only visible under magnification up to x 10
2	just visible with normal corrected vision
3	clearly visible with normal corrected vision (up to 0.5 mm)
4	0.5 mm to 5 mm
5	larger than 5 mm

[a] Unless otherwise specified in subsequent parts of this International Standard

Table 3.4 Rating scheme for designating the intensity of changes (ISO 4628-1)

Rating	Intensity of change
0	unchanged, i.e. no perceptible change
1	very slight, i.e. just perceptible change
2	slight, i.e. clearly perceptible change
3	moderate, i.e. very clearly perceptible change
4	considerable, i.e. pronounced change
5	very marked change

Table 3.5 Degree of rusting and rested area (ISO 4628-3)

Rating	Rusted area (%)
Ri 0	0
Ri 1	0.05
Ri 2	0.5
Ri 3	1
Ri 4	8
Ri 5	40 to 50

Table 3.6 Rating scheme for designating the quantity of cracks (ISO 4628-4)

Rating	Quantity of cracks
0	none, i.e. no detectable cracks
1	very few, i.e. small, barely significant number of cracks
2	few, i.e. small but significant number of cracks
3	moderate number of cracks
4	considerable number of cracks
5	dense pattern of cracks

Table 3.7 Rating scheme for designating the size of cracks (ISO 4628-4)

Rating	Size of cracks
0	not visible under x magnification
1	only visible under magnification up to x 10
2	just visible with normal corrected vision
3	clearly visible with normal corrected vision
4	large cracks generally up to 1 mm wide
5	very large cracks generally more than 1 mm wide

Table 3.8 Rating scheme for designating the quantity of flaking (ISO 4628-5)

Rating	Flaking area (%)
0	0
1	0.1
2	0.3
3	1
4	3
5	15

Table 3.9 Rating scheme for designating the size of areas exposed by flaking (ISO 4628-5)

Rating	Size of flaking areas (largest dimension)
0	not visible under x 10 magnification
1	up to 1 mm
2	up to 3 mm
3	up to 10 mm
4	up to 30 mm
5	larger than 30 mm

Chapter 4
Results and Discussion

4.1 Result of the visual inspection

4.1.1 Steel Power Plants

Generally, power plant will be constructing by using a steel section as a material for an exotic structure surrounding the power plant which will become a bracing structure for the parts of a power plant such as a generator section of a power plants, as well as most power plant in Thailand a power plant structure was built by using steel section fabricated or welded from the factory, then transport it to the construction site for the installation work later on. Most of the power plants in Thailand were Thermal power plant (Coal power or Natural gas power).

In this research, five power plants which located in different region around Thailand were visually inspected, since the information from this research could affect the reputation of those power plants and organizations in negative ways, each power plant will be named as “Power plant #” which “#” indicates the represent letter for each power plant from A to E accordingly.

4.1.1.1 Power Plant A

Power Plant A is a thermal power plant (Coal power) located at the east of Thailand close to the sea shore in to the sea, power plant structure was built in 2000 on the total area of 300 acres, coals are transport from Australia across the sea via barge, the coal will be transport to the power plant via belt conveyor. The structural steel was fabricated from the factory, and then installed at the site.

Fig 4.1 shows overall surrounding environment of Power plant A, the very top of the figure shows the seascape and the coal transporting barge from Australia which was conveying the coal in the power plant, the left side of the figure shows a pile of bottom ash from the combustion of the coal, and the bottom side of the figure shows some part of Power Plant A.

Fig 4.1 Overview of Power Plant A (1)

Fig 4.2 shows the overview of the steel structures in Power Plant A, the left figure shows the edge of the coal conveyors used to transport the coal into the power plant, and the right figure shows some part of the steel structure bracing the “Bottom Ash Silo” near a smokestack.

Fig 4.2 Steel structure in Power Plant A (1)

Fig 4.3 shows the steel structures in the inner area of Power Plant A which are the generator section of the power plant, the steel was painted by anti-corrosive paint to prevent the corrosion of the steel surfaces.

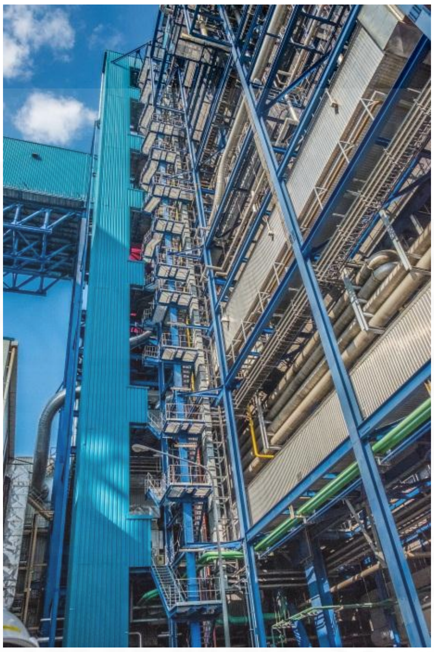


Fig 4.3 Steel structure in Power Plant A (2)

Fig 4.4 shows belt conveyors of Power Plant A, the structure was built outstretched into the sea as the transporting port for coal.

Fig 4.4 Belt conveyors at Power Plant A

Maintenance Personnel Interview

The interviews found that Power Plant A has maintenance routine every one to two years, periodic inspection every year and maintenance every two years, maintenance personnel mainly used visual inspection for the periodic inspection to indicate the deterioration of the steel structure and recorded the inspection result to plan the maintenance routine and repair (if needed) later on.

The maintenance crew said that most of the damages occurred at the steel structure were minor corrosion and minor deterioration of the anti-corrosive paint, and the encounter measure is to remove the rust and the paint from the steel surface and re-paint the steel using anti-corrosive paint based on American standard such as AISC and ASTM, and European standard such as ISO standards.

Steel Surface Inspection and Evaluation Results

The visual inspection results show that the steel structure has minor deterioration of anti-corrosive paint, such as blistering (from high moisture), flaking, cracking, and intensive change in appearance, causing minor corrosion damage on the unprotected steel surface located at the steel section and connection shown in Fig 4.5 to Fig 4.9, the inspection results were recorded in Table 4.1.

Fig 4.5 shows the flaking of an anti-corrosive paint, which covered around 1% of the flaked area with the size of 10 mm flaked areas

Fig 4.5 Flaking of anti-corrosive paint at Power Plant A

Fig 4.6 shows the blistering and rusting damage on the steel anti-corrosive paint and steel surface due to the moisture, size of defect is around 0.5 mm to 5 mm.

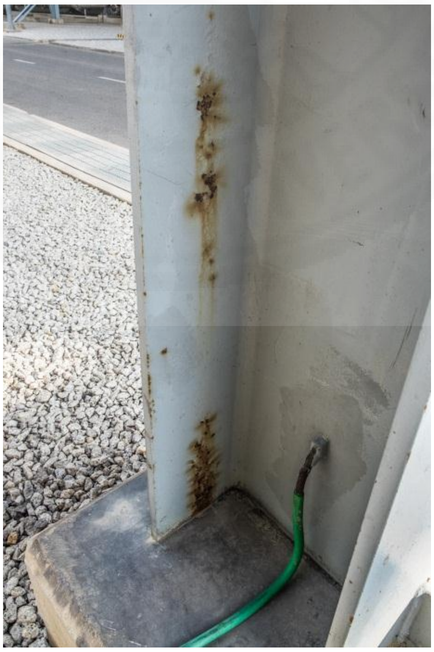


Fig 4.6 Blistering and rusting of anti-corrosive paint at Power Plant A

Fig 4.7 shows perceptible rusting on the steel surface, the rust cover only around 0.5% of the surface, and the size of damage is around 0.5 mm.

Fig 4.7 Rusting of anti-corrosive paint at Power Plant A

Fig 4.8 and Fig 4.9 show the damage on the bolt connection due to the deterioration of the coating and corrosion.

Fig 4.8 Blistering and flaking of paint on bolt at Power Plant A (1)

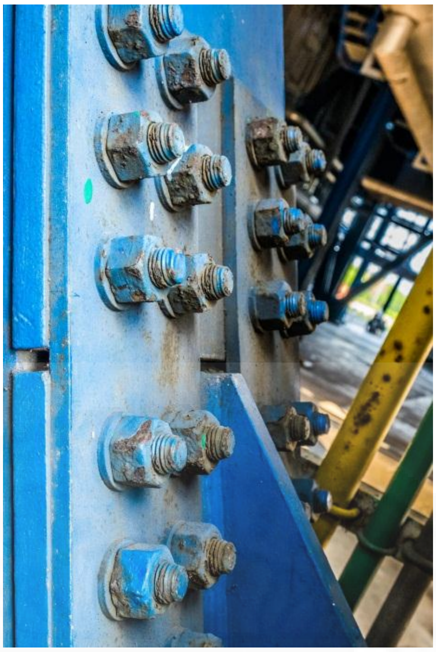


Fig 4.9 Blistering and flaking of paint on bolt at Power Plant A (2)

Table 4.1 represents the surface inspection data such as types of surface damage, degree of damage for each figure using photographic reference method based on ISO 4628 standard.

Table 4.1 Steel Surface Inspection and Evaluation Results (Power Plant A)

Figures	Damage type	Degrees of damage	Photo Ref.*
Fig 4.5	Flaking	Degree of Flaking 3(S3)	Fig. B-13
Fig 4.6	Flaking	Degree of Flaking 4(S3)	Fig. B-12
	Blistering	Degree of Blistering 4(S4)	Fig. B-3
	Rusting	Degree of Rusting Ri 4(S4)	Fig. B-8
Fig 4.7	Rusting	Degree of Rusting Ri 2(S3)	Fig. B-6
Fig 4.8	Flaking	Degree of Flaking 2(S3)	Fig. B-13
	Blistering	Degree of Blistering 4(S4)	Fig. B-3
	Rusting	Degree of Rusting Ri 3(S4)	Fig. B-7
Fig 4.9	Flaking	Degree of Flaking 4(S3)	Fig. B-12
	Blistering	Degree of Blistering 5(S3)	Fig. B-2
	Rusting	Degree of Rusting Ri 4(S3)	Fig. B-8

*Photographic reference in ISO 4628 (shown in Appendix B)

Steel Connection Inspection and Evaluation Results

As mentioned in section 4.1.1 that steel structure in most of the power plants were constructed from the steel sections that were fabricated from the factory, and then installed at the site. Likewise, the steel structure in Power Plant A was welded from the fabrication factory then installed at site using bolt connection.

This constructing method makes the quality of the welds to be good because of the quality control system of the fabrication factory is good (usually fabrication factory used inspection criteria based on American standards or Japanese standards). As well as the weld connection, steel bolt connection is also good since there is no damage or loose bolt found during the inspection, and the coating at the bolt is acceptable since the coating did not damaged during the installation work shows that the coating work is done after the installation as shown in Fig 4.10.

Fig 4.10 Weld and bolt connection of steel column at Power Plant A

Discussion

Overall, Power Plant A has minor deterioration of anti-corrosive paint, such as blistering, flaking, cracking, and intensive change in appearance of the anti-corrosive causing minor corrosion damages on the unprotected steel section and steel bolts, even though the steel connection was constructed nicely by the contractor, but the damage can still be occur if the structure was leftover without any maintenance.

And Even though, Power Plant A has a maintenance routine and inspection every one to two years, but since Power Plant A is lacking of a maintenance personnel and the inspector to perform the maintenance work, makes the maintenance routine to be delay or postpone from the original schedule.

4.1.1.2 Power Plant B

Power Plant B is a power plant that includes thermal power plant (Natural power) and Combine Cycle Gas Turbine Plant: CCGT (Natural gas and steam power), also in the eastern region of Thailand as well as Power Plant A, but located close to the brackish water estuary (mix-water), power plant structure was built in, used natural gas from the Gulf of Thailand as the main source of fuel the generate an electricity. The structural steel was fabricated from the factory, and then installed and painted at the site.

The steel structure in Power Plant B was a constructed by hot-rolled steel as the main structure connected by bolt connection, the structure was located near the brackish water river, so the main damage for the structure in Power Plant B is from Chloride attack. Shown in Fig 4.11 and Fig 4.12 are the steel structure in Power Plant B located near the river.

Fig 4.11 Steel Structure in Power Plant B (1)

Fig 4.12 Steel Structure in Power Plant B (2)

Maintenance Personnel Interview

The interviews found that, Power Plant B has maintenance routine every one to two years, depends on the inspection results, maintenance personnel mainly used visual inspection for periodic inspection to visualize the damage on the steel structure, and then repair the structure (if needed) later on by the external contractor.

The maintenance crew said that, most of the damages occurred at the steel structure were from chloride attack, cause severe corrosion on the steel structure, and the encounter measure is to remove the rust and the paint from the steel surface and re-paint the steel using anti-corrosive paint based on American standard such as AISC and ASTM, if the corrosion consumed the steel sectional area, the steel section must be replaced by the new one, but even though they repaint the steel every one or two years, the steel still deteriorate by the effect of high chloride environment.

Lastly, the maintenance crew said that, if Thailand has standards or guild lines for the inspection, evaluation, and repair for steel structure, they will be glade to use it in their work, but since Thailand had been lacking of standards or guild lines, so they have to use the foreign standards as a references of their work.

Steel Surface Inspection and Evaluation Results

The visual inspection results show that the steel structures had severe corrosion damage on the steel sections and bolt connections. The corrosion covers large area on the steel surface and consumes the steel section as its keep expanding, and some of the area has no coating left on the surface, because of the corrosion on steel surfaces is too severe.

The damage could occurred from poor workmanship during the installation and painting works, because some of the area of steel may have some moisture on its surface before the paint work, or some of the area could be unprotected, because of the paint may not cover the whole area of the steel, especially at the steel connection area, such as under or between the bolt, and between the connection of the steel column to the footing, so the moisture can penetrate into the unprotected area and cause severe corrosion.

Shown in Fig 4.13 to Fig 4.15 is the corrosion damage on steel bolt connections, the corrosion covers on both bolt itself and the steel plate which used to connect each steel section with the bolt, some of the connection was entirely covered by corrosion.

Fig 4.13 Severe corrosion on steel bolt connection in Power Plant B

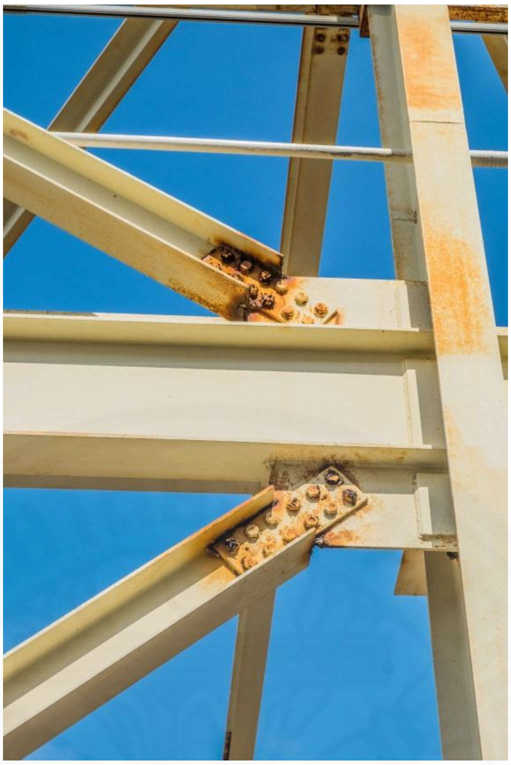


Fig 4.14 Corrosion on the steel bolt connection at Power Plant B (1)

Fig 4.15 Corrosion on the steel bolt connection at Power Plant B (2)

Shown in Fig 4.16 to Fig 4.19 is the corrosion damage at the bottom of the column where the column and the steel plate on the footing were connected, the connection used in these figures were bolt connection, the bottom of the column was not welded to the steel plate as shown in Fig 4.20, but the column was fixed to the footing by bolt.

Fig 4.16 Corrosion on the steel column connection at Power Plant B

Fig 4.17 Corrosion on the steel column connection at Power Plant B

Fig 4.18 Corrosion at the bottom of the column in Power Plant B (1)

Fig 4.19 Corrosion at the bottom of the column in Power Plant B (2)

Fig 4.20 Space between steel column and steel plate in Power Plant B

Table 4.2 represents the surface inspection data such as types of surface damage, degree of damage for each figure using photographic reference method based on ISO 4628 standard.

Table 4.2 Steel Surface Inspection and Evaluation Results (Power Plant B)

Figures	**Damage type**	**Degrees of damage**		**Photo Ref.***
Fig 4.13	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	5(S5)	Fig. B-12
Fig 4.14	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	5(S5)	Fig. B-12
Fig 4.15	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	5(S5)	Fig. B-12
Fig 4.16	Blistering	Degree of Blistering	4(S5)	Fig. B-4
	Rusting	Degree of Rusting	Ri 4(S5)	Fig. B-8
	Flaking	Degree of Flaking	4(S5)	Fig. B-12
Fig 4.17	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
Fig 4.18	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
Fig 4.19	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	4(S5)	Fig. B-12

*Photographic reference in ISO 4628 (shown in Appendix B)

Steel Connection Inspection and Evaluation Results

Unlike the other power plants, the steel structure in Power Plant B was welded, bolted, and painted at the site. This may explain the reason why the steel structure in Power Plant B got many damage and defect. Even though, weld and bolt connection was acceptable (shown in Fig 4.34), but poor paint workmanship could cause a lot of problem to the steel structure.

Fig 4.21 Weld and bolt connection of steel column at Power Plant B

Discussion

Overall, Power Plant B has major corrosion damage on most of the steel sections and steel connections cause by the heavy chloride environment around the structure, and poor workmanship during the installation and painting work, causing severe damage to the structure especially at the steel connection such as bolt connections and the bottom of the column connections.

And Even though, Power Plant B has a maintenance routine and inspection every one to two years, but because of the heavy environment at Power Plant B and the poor workmanship back in the construction work, makes the steel structure at Power Plant B deteriorate rapidly.

4.1.1.3 Power Plant C

Power Plant C is a thermal power plant (coal power) located at the north of Thailand in the mountain areas, power plant structure was built since 1991 and start generated electricity in 1995, the coal was transporting around the plant by belt conveyors then burned, to generated electricity form the thermal power. The power plant was subjected to many Sulfur dioxides (SO_2) from the combustion of coal which could make the steel corrode.

Currently, Power Plant C was having a construction site of a new sub power plant as a replacement power plant for the old one, so the inspection will be divided in to two parts which are the construction site, and the old power plant structure.

Fig 4.22 shows overview of the construction site of a replacement power plant, the structural steel was fabricated from the factory, and then installed at the site.

Fig 4.22 Construction site of Power Plant C

Fig 4.23 and Fig 4.24 shows the overview of the steel structure in the old power plant which was built in 1991.

Fig 4.23 Steel structure in Power Plant C (1)

Fig 4.24 Steel structure in Power Plant C (2)

Maintenance Personnel Interview

The interviews found that, the old steel structure in Power Plant C has no maintenance routine since built. The maintenance crew and civil engineer division claim that, their structures have no severe damage during its service life because of the good construction system and good corrosive prevention system.

The construction system used for steel structure in Power Plant C was shown in the flow chart below (Fig 4.25).

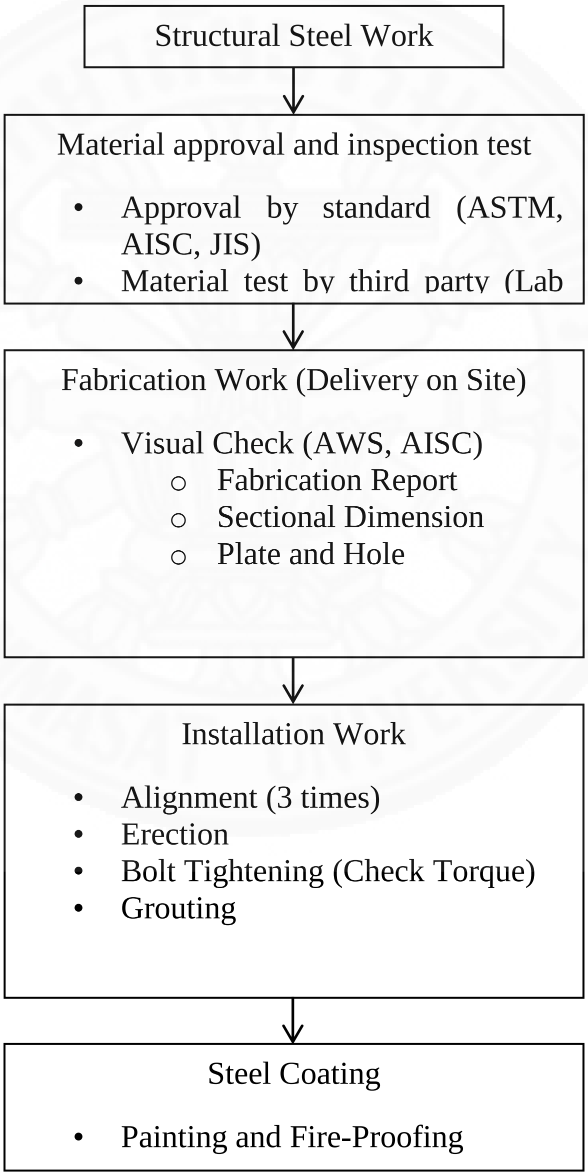


Fig 4.25 Flow chart of construction system used in Power Plant C

Steel Surface Inspection and Evaluation Results

The surface inspection results show that, the steel section at the connection site has no perceptible damage, since the steel was painted by anti-corrosive paint with many layers, shown in Fig 4.26 is the steel section that was fabricated and painted from the factory waiting for installation later on, the paint has many layers such as zinc coating, chromate coating, primer coating, and the paint (Top finish) coating etc.

Fig 4.26 Anti-corrosive coating on the steel section at Power Plant C

But unlike the steel section at the construction site, the steel structures at the old power plant found to be deteriorated due to the corrosion damage from the flaking of the anti-corrosive paint, as shown in Fig 4.27 on the right side of the figure that the surface of the steel was exposed to the environment, and some of the steel section was consume by the corrosion.

Fig 4.27 Flaking and corrosion of the steel coating at Power Plant C

Table 4.3 represents the surface inspection data such as types of surface damage, degree of damage for each figure using photographic reference method based on ISO 4628 standard.

Table 4.3 Steel Surface Inspection and Evaluation Results (Power Plant C)

Figures	Damage type	Degrees of damage		Photo Ref.*
Fig 4.26	Rusting	Degree of Rusting	None	-
	Flaking	Degree of Flaking	1(S1)	Fig. B-12
Fig 4.27	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	4(S5)	Fig. B-12

*Photographic reference in ISO 4628 (shown in Appendix B)

Lastly, the other damage found besides corrosion and deterioration of anti-corrosive coating on the steel surface are at the belt conveyors, shown in Fig 00 and Fig 00 that, on the steel structure surface was covered by dust and coal which cause the steel to be deteriorated.

Fig 4.28 Deterioration on the steel conveyor at Power Plant C (1)

Fig 4.29 Deterioration on the steel conveyor at Power Plant C (2)

Steel Connection Inspection and Evaluation Results

The steel connection inspection results show that, in the construction site at Power Plant C had a good steel connection, as shown in Fig 4.30 the contractor used the indicator washers to indicate the tightness of the bolt connection, and the bolt was marked (shown in Fig 4.31 and Fig 4.32) after the bolt inspection (torque checking).

Fig 4.30 Indicator washer used in bolt connection at Power Plant C

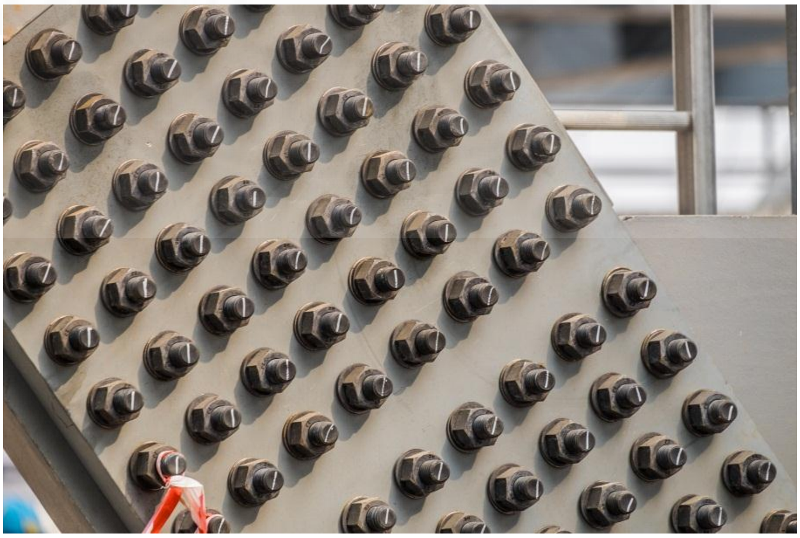


Fig 4.31 Marks on the bolt connection at Power Plant C (1)

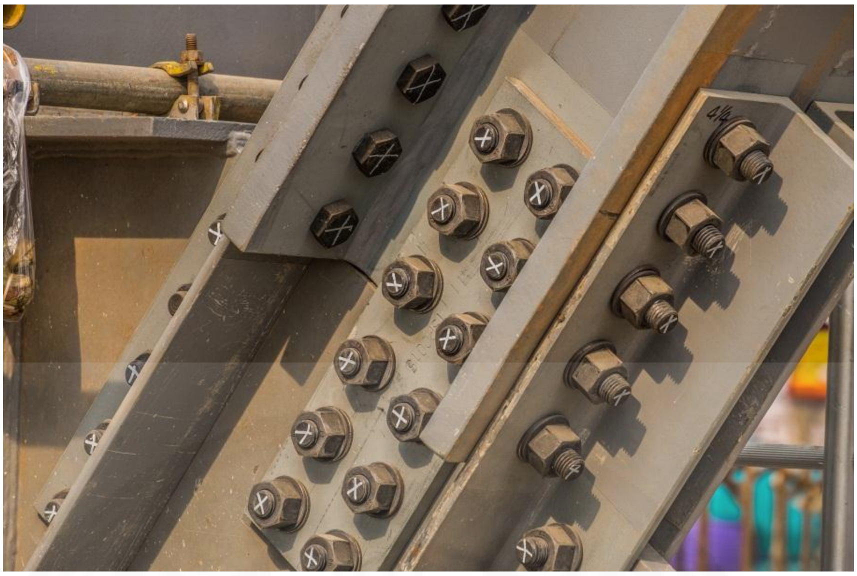


Fig 4.32 Marks on the bolt connection at Power Plant C (2)

The steel connection in the old power plant in Power Plant C (Fig 4.33 Steel weld and bolt connection at Power Plant C), has acceptable quality, since the steel section was fabricated from the factory and installed at the site.

Fig 4.33 Steel weld and bolt connection at Power Plant C

Discussion

Power Plant C shows both poor maintenance system and good construction system in the same time, since they have no maintenance routine for their steel structure since built, makes the steel structure in the old power plant to be damaged and deteriorated from the corrosion.

But construction system of the new power plant was good, because the contractor was emphasized on the inspection and checking of the steel structure from the start of the processes which are material properties testing and fabrication checking, to the end of the construction processes which are the steel structure installation and the anti-corrosive painting, to make sure that the structure will be constructed correctly.

Even though, there is no maintenance routine for the steel structure in Power Plant C, but with good construction system should makes the durability of the structure to be substantial as the design specification.

4.1.1.4 Power Plant D

Power Plant B are thermal power plant (Natural gas power) and Combine Cycle Gas Turbine Plant: CCGT (Natural gas and steam power) located at the south of Thailand close to the estuary, power plant structure was built in 1996 on the total area of 484 acres, natural gas was transported from the Gulf of Thailand via pipeline, the power plant structure was special assemble imported from Japan, and constructed on the large vessel. The steel structure of Power Plant D was shown in Fig 4.34.

Fig 4.34 Steel Structure in Power Plant D

Maintenance Personnel Interview

The interviews found that Power Plant D has maintenance routine and periodic inspection every five years, maintenance personnel mainly used visual inspection for the periodic inspection to indicate the deterioration of the steel structure and recorded the inspection result to plan the maintenance routine and repair (if needed) later on, the reason that the maintenance routine and inspection for Power Plant D is perform five years a time, because of the maintenance crew used effective preventive measure such as Cathodic protection (CP), Anti-corrosive Painting, and Galvanize coating to prevent the steel from corrosion due to the severe environment.

The maintenance crew said that most of the damage occurred at the steel structure were minor corrosion and minor deterioration of the anti-corrosive paint, and the encounter measure is to remove the rust and the paint from the steel surface and re-paint the steel using anti-corrosive paint from a good manufacture.

Steel Surface Inspection and Evaluation Results

The visual inspection results show that the steel structure has minor deterioration of anti-corrosive paint such as, flaking, and intensive change in appearance (color), causing minor corrosion damage on the unprotected steel surface located at the steel section and connection shown in Fig 4.35 to Fig 4.37, the inspection results were recorded in Table 4.4.

Fig 4.35 Flaking of anti-corrosive paint at Power Plant D

Fig 4.36 shows the corrosion damage on the weld surface of a beam-column structure in Power Plant D.

Fig 4.36 Rusting on the welded connection of steel at Power Plant D

As shown in Fig 4.37, the intensity change of anti-corrosive paint due to the deterioration of the paint over long usage without maintenance work.

Fig 4.37 The intensity change of anti-corrosive paint in Power Plant D

Table 4.4 Steel Surface Inspection and Evaluation Results (Power Plant D)

Figures	Damage type	Degrees of damage		Photo Ref.*
Fig 4.35	Flaking	Degree of Flaking	1(S2)	Fig. B-12
	Rusting	Degree of Rusting	Ri 1(S2)	Fig. B-5
Fig 4.36	Rusting	Degree of Rusting	Ri 4(S4)	Fig. B-8
Fig 4.37	Intensive of change	Change in intensity of color	2	-

*Photographic reference in ISO 4628 (shown in Appendix B)

Steel Connection Inspection and Evaluation Results

As mentioned in section 4.1.1 that steel structure in most of the power plants were constructed from the steel sections that were fabricated from the factory, and then installed at the site. Likewise, the steel structure in Power Plant D was welded from the fabrication factory (Fig 4.38) then installed at site using bolt connection (Fig 4.39). This construction method makes the quality of the welds to be good because of the quality control of the fabrication factory is good. Also, as shown in Fig 4.38 and Fig 4.39 that the anti-corrosive paint has no perceptible change in appearance (color) since these steel structures got maintenance (re-paint) recently, different from the steel in Fig 4.37 which haven't got any maintenance yet.

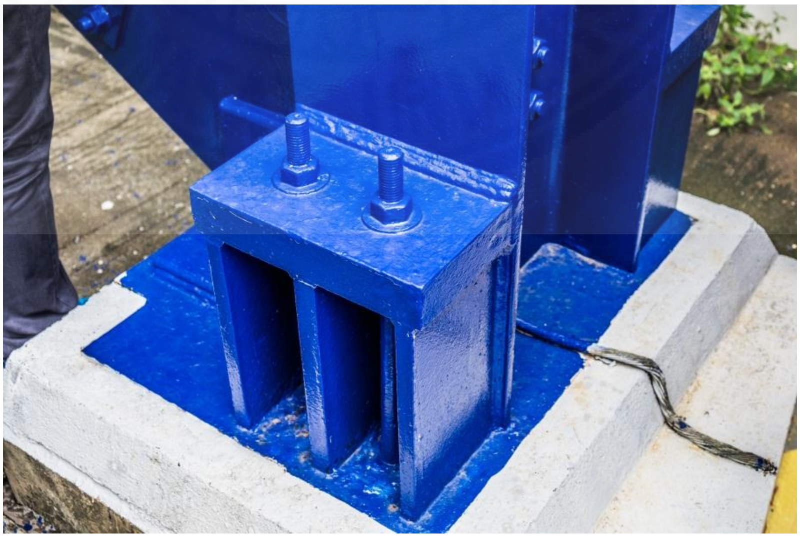


Fig 4.38 Steel welded connection at Power Plant D

Fig 4.39 Steel bolted connection at Power Plant D

Discussion

Overall, the steel structure in Power Plant D was highly protected by anti-corrosive paint, so there is not much of corrosion damage found, only very slight perceptible damage was found which are flaking of anti-corrosive paint and some rusting on the weld surface at the beam-column.

Even though Power Plant D has five years period of maintenance routine and has a river as surrounding environment, but Power Plant D still had a very few damage occurred on to the steel structure, because of a good maintenance crew and effective corrosion preventive measures such as a good anti-corrosive paint material and good workmanship on painting work, makes the steel structure to be well protected and has a longer service live.

4.1.1.5 Power Plant E

Power Plant E are thermal power plant (Natural gas power located at the south of Thailand close to the river, power plant structure was built in 1973, natural gas was transported from the Gulf of Thailand via pipeline, the power plant structure was fabricated, and installed at the. The overview of the steel structure in Power Plant E was shown in Fig 4.40.

Fig 4.40 Overview of the steel structure in Power Plant E

Maintenance Personnel Interview

The interviews found that Power Plant E has a steel structure periodic inspection every year, inspector mainly used visual inspection for the periodic inspection to indicate the deterioration of the steel structure, but maintenance routine and repair (if needed) will be done only if the structure got a severe damage.

The maintenance crew said that most of the damage occurred at the steel structure were minor corrosion and minor deterioration of the anti-corrosive paint, and the encounter measure is to remove the rust and the paint from the steel surface and re-paint the steel using anti-corrosive paint from a good manufacture.

Steel Surface Inspection Results

The visual inspection results show that the steel structure had many damage on the anti-corrosive paint such as, flaking, cracking, blistering, rusting, and intensive change in appearance (color). The damage located at the steel surface and at the steel connection. The inspection results were recorded in Table 4.5.

Fig 4.41 shows severe corrosion on the steel column in Power plant due to the small and dense blistering of the anti-corrosive paint.

Fig 4.41 Corrosion on the steel column in Power Plant E

Fig 4.42 shows some minor rusting and blistering at the steel bolt connection occurred from the moisture that penetrate in to the steel connection.

Fig 4.42 Rusting and blistering on the steel bolt in Power Plant E

Fig 4.43 shows some cracking of the anti-corrosive paint due to the high temperature of surrounding environment.

Fig 4.43 Cracking of the anti-corrosive paint in Power Plant E

Fig 4.44 shows the corrosion damage on the steel bolt, occurred by the moisture that penetrated into the gap between the bolt and the steel plant, this case can happen when the bolt connection was not painted entirely (missed at the gap), makes some area of the steel to be unprotected.

Fig 4.44 Corrosion damage on the bolt connection at Power Plant E

Fig 4.45 shows the corrosion damage on the steel plate, occurred by the moisture that penetrated into the steel surface that was exposing by the flaking of the anti-corrosive paint.

Fig 4.45 Flaking of the anti-corrosive paint as Power Plant E

Table 4.5 represents the surface inspection data such as types of surface damage, degree of damage for each figure using photographic reference method based on ISO 4628 standard.

Table 4.5 Steel Surface Inspection and Evaluation Results (Power Plant E)

Figures	**Damage type**	**Degrees of damage**		**Photo Ref.***
Fig 4.41	Rusting	Degree of Rusting	Ri 4(S5)	Fig. B-8
	Blistering	Degree of Blistering	5(S4)	Fig. B-3
Fig 4.42	Rusting	Degree of Rusting	Ri 2(S3)	Fig. B-6
	Blistering	Degree of Blistering	2(S3)	Fig. B-2
Fig 4.43	Cracking	Degree of Cracking	4(S2)	Fig. B-10
	Rusting	Degree of Rusting	Ri 2(S3)	Fig. B-6
Fig 4.44	Flaking	Degree of Flaking	4(S5)	Fig. B-12
	Rusting	Degree of Rusting	Ri 5(S4)	Fig. B-9
Fig 4.45	Flaking	Degree of Flaking	4(S4)	Fig. B-12
	Rusting	Degree of Rusting	Ri 4(S4)	Fig. B-8

*Photographic reference in ISO 4628 (shown in Appendix B)

Steel Connection Inspection and Evaluation Results

Steel connection inspection results show that the steel connection used in Power Plant E are mostly bolted connection which were constructed nicely (shown in Fig 4.46), but some of the connection of a steel structure in Power Plant E was welded together at the site (as shown in Fig 4.47) since the quality of the welds is not good bur still in the acceptable range.

Fig 4.46 Bolt connection of the steel structure in Power Plant E

Fig 4.47 Weld connection of the steel structure in Power Plant E

Discussion

Overall, Power Plant E has many corrosion damage and defect with the anti-corrosive paint such as blistering, flaking, cracking, and rusting which could weaken the structure in the future.

Even tough, Power Plant E inspect there structure every year, but to maintenance the structure only they when got severe damage is not a good ways to handle the damage efficiently, because these damages could develop to the more and more severe damage that could leads to the loss of steel section from the corrosion, which will cause a lot of money to repair the structure in the future.

4.1.2 Steel Highway Bridges A and B

Highway Bridge in Thailand mostly is concrete structures, but there are a few Highway Bridge that were constructed buy steel, some due to the lane expansions. In this research, two steel highway bridge which located in the middle of Thailand were visually inspected, since the information from this research could affect the reputation of those steel highway bridge and organizations in negative ways, each steel highway bridge will be named as “Highway bridge #” which “#” indicates the represent letter for each steel highway bridge from A and B accordingly.

Highway Bridge A and Highway Bridge B are located in Bangkok, Thailand. The bridge were constructed by using steel as the main material, and coated with paint to protect the surface of the steel from the environment. The overviews of the highway bridge were shown in Fig 4.48 for Highway Bridge A and Fig 4.49 for Highway Bridge B.

Fig 4.48 Overview of Highway Bridge A

Fig 4.49 Overview of Highway Bridge B

Maintenance Personnel Interview

From interviewing the personnel who responsibility to maintenance work for the steel highway bridge, the results found that inspection routine for the steel highway bridge were divided into four types which are

1. Daily inspection: performing visual inspection in a patrol car, looking for major damage and take photos.
2. Periodic inspection: primary inspection to maintain steel highway bridge durability, the frequency of inspection per year depends on the difficulty of the location accessibility, Risks, and the possibility of structural damage.
3. Special inspection: the additional inspection using more advance testing apart from daily inspection to ensure the safety of the customers.
4. Emergence inspection: a visual inspection after the event of natural disasters or fatal accident on the steel highway bridge to initially check the steel highway bridge before special inspection to consider emergency repair.

The damage will be divided into four level calls “A (Poor Condition)”, “B (Fair Condition)”, “C (Good Condition)”, and “D (Very Good Condition)”. The evaluation of damage can be carry out by using photographic reference methods.

Steel Surface Inspection and Evaluation Results

Inspection of steel highway bridge has to carry out by using patrol car for transportation around the site and parked in the parking zone under the highway bridge for safety, the result shows that for steel Highway Bridge A is in fair condition, minor damage found on the steel structure are mostly coating damage from the deterioration of the paint and some of the lichen cover the surface of the steel (high humidity area) as shown in Fig 4.50 and Fig 4.51.

Fig 4.50 Flaking of paint on steel surface at Highway Bridge A

Fig 4.51 Lichen on the steel surface at Highway Bridge A

Highway Bridge B was repainted recently according to the maintenance routine, so the surface of the steel was well protected as shown in Fig 4.52 and Fig 4.53

Fig 4.52 Painted steel surface of Highway Bridge B (1)

Fig 4.53 Painted steel surface of Highway Bridge B (2)

Table 4.6 represents the surface inspection data such as types of surface damage, degree of damage for each figure using photographic reference method based on ISO 4628 standard.

Table 4.6 Steel Surface Inspection and Evaluation Results (Highway Bridge A and B).

Figures	**Damage type**	**Degrees of damage**	**Photo Ref.***
Fig 4.50	Flaking	Degree of Flaking 5(S5)	Fig. B-12
Fig 4.51	Intensive of change	Change in intensity of color 5	-
Fig 4.52	No damage	-	-
Fig 4.53	No damage	-	-

*Photographic reference in ISO 4628 (shown in Appendix B)

Steel Connection Inspection and Evaluation Results

The connection of the steel both weld and bolt are acceptable according to the criteria in DPT 1561-51 and AWS D1.1/D1.1M for welding visual inspection, and in JASS 6 for bolting inspection, since the steel structure of the steel highway bridge was fabricated from the factory and then installed at the site, so the quality of the welding and bolting connection is good as shown in Fig 4.540 to Fig 4.56.

Fig 4.54 Bolt connection of steel girder at Highway Bridge A

Fig 4.55 Bolt connection of steel girder at Highway Bridge B

Fig 4.56 Weld connection of the steel section at Highway Bridge B

Discussion

Both steel highway bridge were constructed nicely, and the maintenance personnel are following a good guideline makes the maintenance work to be rewarding, but even though with the maintenance guild line, Highway Bridge A still has clearly deterioration of paint, the reason for this is “lack of skill worker”, since with the limited amount of the worker comparing with the amount of the highway bridges, makes the maintenance work will be delay, just like the case of Highway Bridge A.

4.1.3 Steel Billboard A

The steel billboard in Thailand mostly are privately owned, so it is depend on owner judgment whether to maintenance it or not. And since steel billboard structure does not have to carry too much load so steel billboard maintenance is in low priority, even though recently in Thailand there is an accident of steel billboard collapsing down causing damage to the property. In this research, steel billboard which located in Rangsit area was visually inspected, since the information from this research could affect the reputation of the billboard owner in negative ways, the billboard will be named as “Billboard A”.

The inspection criteria were carried out by using the criteria in DPT 1561-51 for welding visual inspection, and ISO 4628 for steel anti-corrosive paint inspection. The billboard was located near the road. Fig 4.57 shows the overview to the structure of Billboard A, the content in the billboard was covered for the reputation issue.

Fig 4.57 Structure overview of Billboard A

Maintenance Personnel Interview

This structure was private properties and was abandoned, so the interview data cannot be obtained for this site.

Steel Surface Inspection and Evaluation Results

The inspection results show some severe paint defects such as flaking and blistering, as well as corrosion damage on the surface of the steel as shown in Fig 4.58 to Fig 4.66, and the inspection and evaluation results were recorded in Table 4.7 and Table 4.8.

Fig 4.58 Blistering and rusting of paint on Billboard A (1)

Fig 4.59 Blistering and rusting of paint on Billboard A (2)

Fig 4.60 Blistering and rusting of paint on Billboard A (3)

Fig 4.61 Flaking and rusting of paint on Billboard A (1)

Fig 4.62 Flaking and rusting of paint on Billboard A (2)

Fig 4.63 Flaking and rusting of paint on Billboard A (3)

Fig 4.64 Flaking and rusting of paint on Billboard A (4)

Fig 4.65 Flaking and rusting of paint on Billboard A (5)

Fig 4.66 Flaking of paint on Billboard A

Table 4.7 represents the surface inspection data such as types of surface damage, degree of damage for each figure using photographic reference method based on ISO 4628 standard.

Table 4.7 Steel Surface Inspection Results (Billboard A)

Figures	Damage type	Degrees of damage		Photo Ref.*
Fig 4.58	Rusting	Degree of Rusting	Ri 4(S4)	Fig. B-8
	Blistering	Degree of Blistering	4(S4)	Fig. B-3
Fig 4.59	Rusting	Degree of Rusting	Ri 3(S4)	Fig. B-7
	Blistering	Degree of Blistering	3(S4)	Fig. B-3
Fig 4.60	Rusting	Degree of Rusting	Ri 3(S4)	Fig. B-7
	Blistering	Degree of Blistering	5(S5)	Fig. B-4
Fig 4.61	Rusting	Degree of Rusting	Ri 4(S5)	Fig. B-8
	Flaking	Degree of Flaking	5(S5)	Fig. B-12
Fig 4.62	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	5(S5)	Fig. B-12
Fig 4.63	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	5(S5)	Fig. B-13
Fig 4.64	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	5(S5)	Fig. B-13
Fig 4.65	Rusting	Degree of Rusting	Ri 5(S5)	Fig. B-9
	Flaking	Degree of Flaking	5(S5)	Fig. B-13
Fig 4.66	Flaking	Degree of Flaking	4(S3)	Fig. B-12

*Photographic reference in ISO 4628 (show in Appendix B)

Steel Connection Inspection and Evaluation Results

Billboard A was thoroughly inspected base on DPT 1561-51 visual inspection criteria and evaluated based on each type of welding defects similarly to the billboard inspection.

The inspection results show many serious weld defects mainly porosities and undercuts at the welding, the inspection results was recorded in the form of table (Table 4.8), which shown the size of the defect (depth and diameter) on each welds in relation with the figures of each joint, as in the figure shows the location of defect (see Fig 4.67 to Fig 4.72).

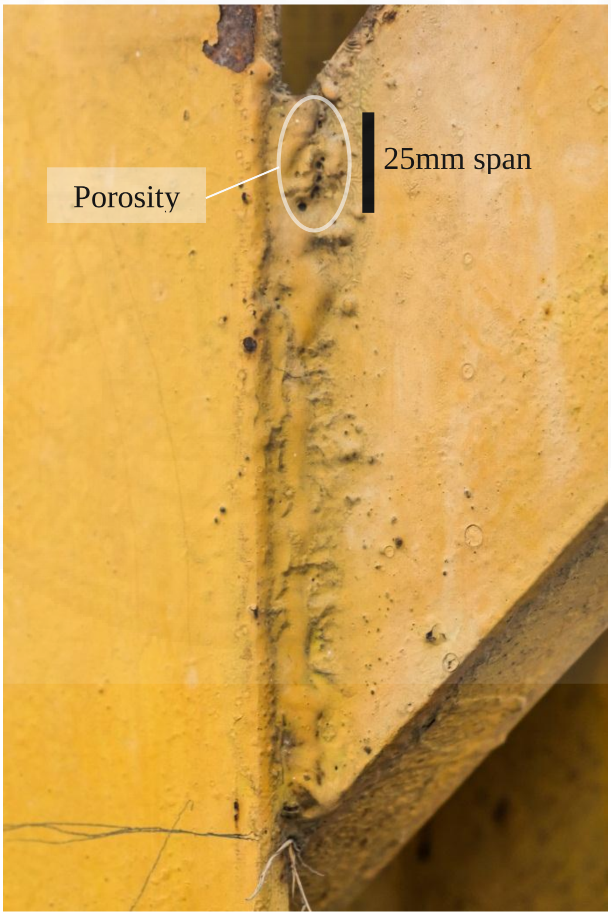


Fig 4.67 Welding defects on Billboard A (joint 1)

Fig 4.68 Welding defects on Billboard A (joint 2)

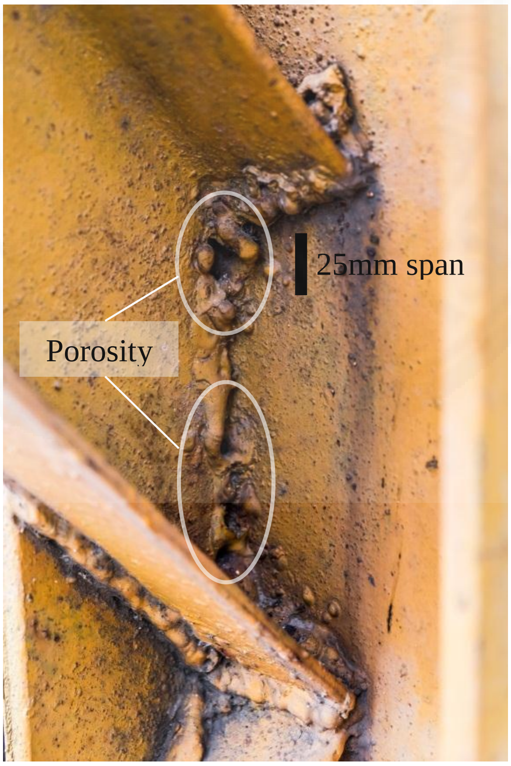


Fig 4.69 Welding defects on Billboard A (joint 3)

Fig 4.70 Welding defects on Billboard A (joint 4)

Fig 4.71 Welding defects on Billboard A (joint 5)

Shown in Fig 4.72 is a defect from poor workmanship which called “no-weld”, the steel section has no weld to connect them together makes the load transformation to be disable.

Fig 4.72 Welding defects on Billboard A (joint 6)

Table 4.8 Welding Inspection Results (Billboard A)

Figures	Thickness of Steel (mm)	Size of weld (mm)	Type of Weld	Defect of Weld [a]		
				Crack	Porosity [b] (mm)	Undercut [c] (mm)
Fig 4.67	10.0	150	Fillet Weld	-	10.5	-
Fig 4.68	10.0	150	Fillet Weld	-	-	2.5
Fig 4.69	7.5	150	Fillet Weld	-	15.0	-
Fig 4.70	10.0	75	Fillet Weld	-	-	3.0
Fig 4.71	10.0	150	Fillet Weld	-	12.5	-

[a] Shaded area means "Unacceptable" according to DPT 1561-51
[b] Values specified in this column is the sum of diameter of the porosity/inch (25mm)
[c] Values specified in this column is the maximum depth of undercut

Discussion

Overall, the inspection found a lot of welding defects due to poor workmanship, and significant amount of corrosion damage due to the deterioration of anti-corrosive paint. All of the welding defects occurred on the construction process which is significantly severe, but the corrosion damage is even more severe because the corrosion can decrease the steel sectional area and cause the structure to be weaker and weaker over time.

The cause of this structure damage is poor workmanship since the beginning of the construction process and no maintenance action from the owner, but since the structure was private owing, it's the owner rights to choose if the maintenance work is going to happen or not.

4.1.4 Steel Buildings

In this research, four steel buildings were visually inspected, including two steel roof and two steel low-rise building, since the information from this research could affect the reputation of those buildings and organizations in negative ways, each steel building will be named as "Structure #" which "#" indicates the represent letter for each building as A and B accordingly.

4.1.4.1 Steel Roof of office Building (Roof structure A)

Roof structure A is a steel roof structure of an office building, which was located at the north of Thailand, the main structure was constructed in 1994 by using concrete, but the roof structure was constructed by using steel section such as H-beam and Channel section, connected together by weld connection, the roof structure was welded at the site.

Fig 4.73 shows the structure outside of the Roof Structure A, concisely roof structure A is a square shaped building with a space in the middle.

Fig 4.73 Overview of the Roof Structure A

Maintenance Personnel Interview

Information from the interview indicated that, since the roof structure is a primary structure that does not have to carry too much load, causes a priority to maintenance the steel structure itself to be neglected and most of the roof structure have not been maintenance or inspect since it's built. The roof structure was constructed as the site by welding (poor quality control).

Steel Surface Inspection and Evaluation Results

The inspection results show great amount of corrosion on the steel surface and some damage occurred on the steel section from the welding process

From Fig 4.74 to Fig 4.79 show the corrosion damage on the steel surfaces, and perceptible change in intensity of the steel coating.

Fig 4.74 Corrosion on the steel column at Roof Structure A (1)

Fig 4.75 Corrosion on the steel column at Roof Structure A (2)

Fig 4.76 Corrosion on the steel column at Roof Structure A (3)

Fig 4.77 Corrosion on the steel column at Roof Structure A (4)

Fig 4.78 Corrosion on the steel beam at Roof Structure A

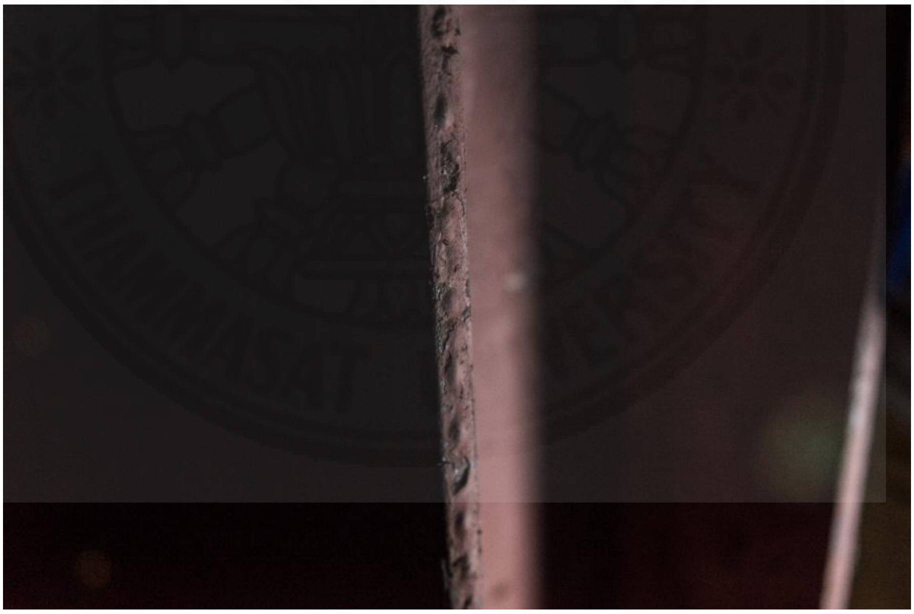


Fig 4.79 Blistering of paint on steel column at Roof Structure A

Table 4.9 represents the surface inspection data such as types of surface damage, degree of damage for each figure using photographic reference method based on ISO 4628 standard.

Table 4.9 Steel Surface Inspection and Evaluation Results (Roof Structure A)

Figures	Damage type	Degrees of damage		Photo Ref.*
Fig 4.74	Rusting	Degree of Rusting	Ri 3(S4)	Fig. B-7
	Intensive of change	Change in intensity of color	3	-
Fig 4.75	Rusting	Degree of Rusting	Ri 3(S4)	Fig. B-7
	Flaking	Degree of Flaking	4(S5)	Fig. B-12
	Intensive of change	Change in intensity of color	3	-
Fig 4.76	Rusting	Degree of Rusting	Ri 3(S4)	Fig. B-7
	Intensive of change	Change in intensity of color	3	-
Fig 4.77	Rusting	Degree of Rusting	Ri 5(S4)	Fig. B-9
	Intensive of change	Change in intensity of color	2	-
Fig 4.78	Rusting	Degree of Rusting	Ri 5(S4)	Fig. B-9
	Intensive of change	Change in intensity of color	3	-
Fig 4.79	Blistering	Degree of Blistering	4(S4)	Fig. B-3
	Intensive of change	Change in intensity of color	2	-

*Photographic reference in ISO 4628 (shown in Appendix B)

The inspection results show the damage from the welding process during the construction, the arc of the weld was melted the steel section out and penetrated the steel section as shown in Fig 4.80 to Fig 4.82. This type of damage came from poor workmanship of the welder.

Fig 4.80 Damage from welding process on the steel column (1)

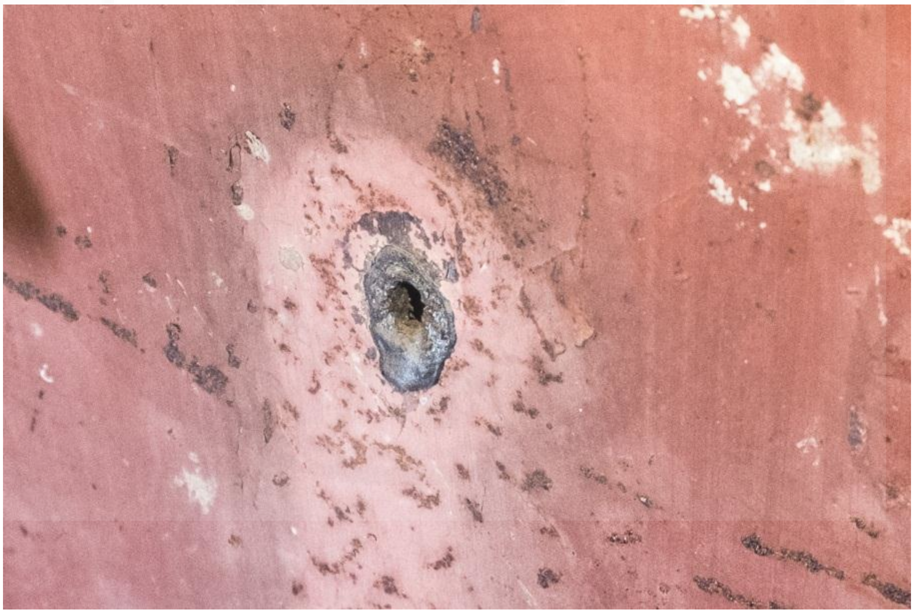


Fig 4.81 Damage from welding process on the steel column (2)

Fig 4.82 Damage from welding process on the steel column (3)

Steel Connection Inspection and Evaluation Results

The steel connection results show that the weld connection on the roof structure is not good based on its appearance, since the connection was constructed at the site, so the quality control is poor so as the workmanship of the workers. Fig 4.83 shows the steel welded connection (beam-column) of the roof structure.

Fig 4.83 Weld connection of beam-column at Roof Structure A

Discussion

Since the structure that was inspected is very big, so the inspections were carried out section by section cover around 25 percent of the whole structures, and because of the difficulty of the accessibility of the location and poor illumination under the roof structure area, causing the welding inspection and paint inspection to be impracticable.

Without any maintenance or inspection activity since built, the result shows that the quality of the connection (all weld connection) is poor and many damages cause by welding procedure had been found such as a burning point or hole on the steel section, and the melted or cut spot on the steel sections, this damages and defects occurred since the construction process and was not fix until now.

Even though, the roof structure does not have to carry too much loads, but with the damages like in this Roof Structure A, the damage could grow and eventually the structure will collapses down.

4.1.4.2 Steel Roof of Auditorium Building (Roof Structure B)

Roof Structure B is the steel roof of a auditorium building, which was located on the north of Thailand, constructed by steel pipe with weld connection, as shown in Fig 4.84 and Fig 4.85 are the overview of the roof structures of this building.

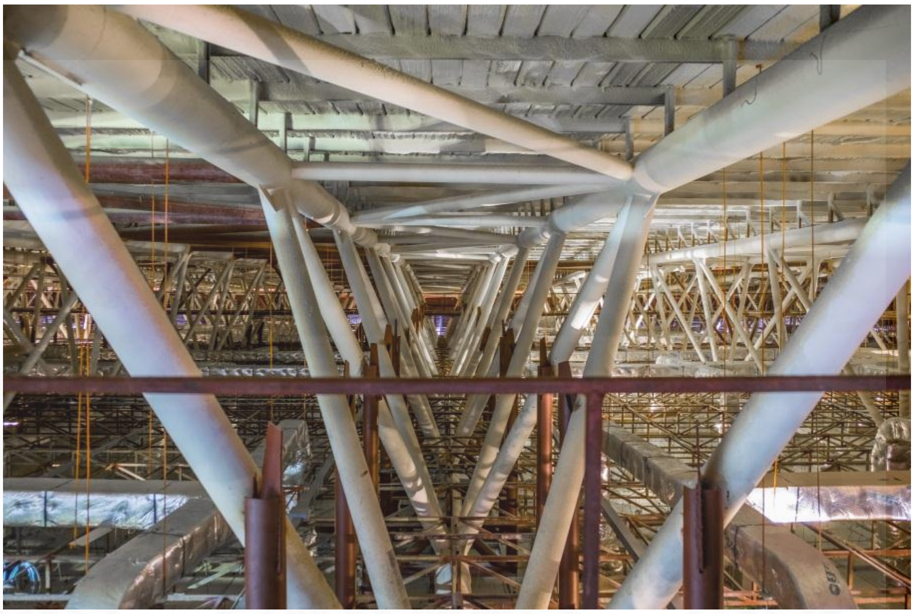


Fig 4.84 Overview of Roof Structure B (1)

Fig 4.85 Overview of Roof Structure B (2)

Maintenance Personnel Interview

The interview results indicated that the structure did not have any maintenance for the roof structure since the structure was built, and there are no structure engineer working for this structure.

But since the structure was located at the northern region of Thailand, and the structure was not exposed to the environment directly, and with the steel coating makes the steel is well protected from the corrosion damage.

Steel Surface Inspection and Evaluation Results

As mentioned in the previous section, the surface of the steel was coated with fire-proof coating, and with the low humidity environment makes the steel to be well protected from corrosion damage.

The steel coating has no damage at all, only a slight change in intensity of appearance (color) as shown in Fig 4.86.

Fig 4.86 Intensity change of steel coating at Roof Structure B

Steel Connection Inspection and Evaluation Results

The inspection results show many welding defects and many poor constructed welds; since the structure was welded at the site makes the quality of the weld and welding workmanship to be poor.

Weld defect pound on the weld surface is mostly undercuts and porosity as shown in Fig 4.87 and Fig 4.87. Also the sign of poor workmanship found in this structure is that some of the connection has the discontinuity of weld or incomplete welding as shown in Fig 4.89 to Fig 4.91.

Fig 4.87 Undercut on the steel weld connection as Roof Structure B

Fig 4.88 Small Porosity on the weld connection at Roof Structure B

Fig 4.89 Discontinuity of weld on Roof Structure B (1)

Fig 4.90 Discontinuity of weld on Roof Structure B (2)

Fig 4.91 Missing weld on the beam girder at Roof Structure B

Discussion

Even though the steel structure does not have any damage with the corrosion damage, but the poor workmanship of the welding work caused many defect of the weld on the structure that could high affect the structure capacities.

This type of defect should be fixed in the construction process as the quality control procedure, the structure should be inspection in detail to indicate the defect and repair the defect before the construction work is done.

In this case, even though there aren't any signs of structure failure and the structure can still be used, but these defect should be repair to ensure that the structure is in a save condition.

4.1.4.3 Steel Low-Rise Building A (Steel Structure A)

A simple low-rise building with only one story, the structure was built by welding steel section together at the site, and was built in 2014.

The overview of Steel Structure A is shown in Fig 4.92, the structure was welded at the site then painted with anti-corrosive coating. The weld connection was fillet weld which connect a steel beam and column together (beam-column)

Fig 4.92 Overview of Steel Structure A

Maintenance Personnel Interview

This structure was private properties and was left empty since it was built, so the interview data cannot be obtain for this site.

Steel Surface Inspection and Evaluation Results

The steel surface inspection shows no damage or defect on the steel coating, since this structure was just built and has not been use until now. The surface of the steel was painted nicely as shown in Fig 4.93.

Fig 4.93 Overview of a steel coating as Steel Structure A

Steel Connection Inspection and Evaluation Results

Steel Structure A was thoroughly inspected base on DPT 1561-51 visual inspection criteria and evaluated based on each type of welding defects similarly to the billboard inspection.

The inspection results show many weld defects mainly porosities and undercuts at the welding, the inspection results was recorded in the form of table (Table 4.10), which shows the size of the defect (depth and diameter) on each welds in relation with the figures of each joint, as in the figure shows the location of defect (see Fig 4.94 to Fig 4.101).

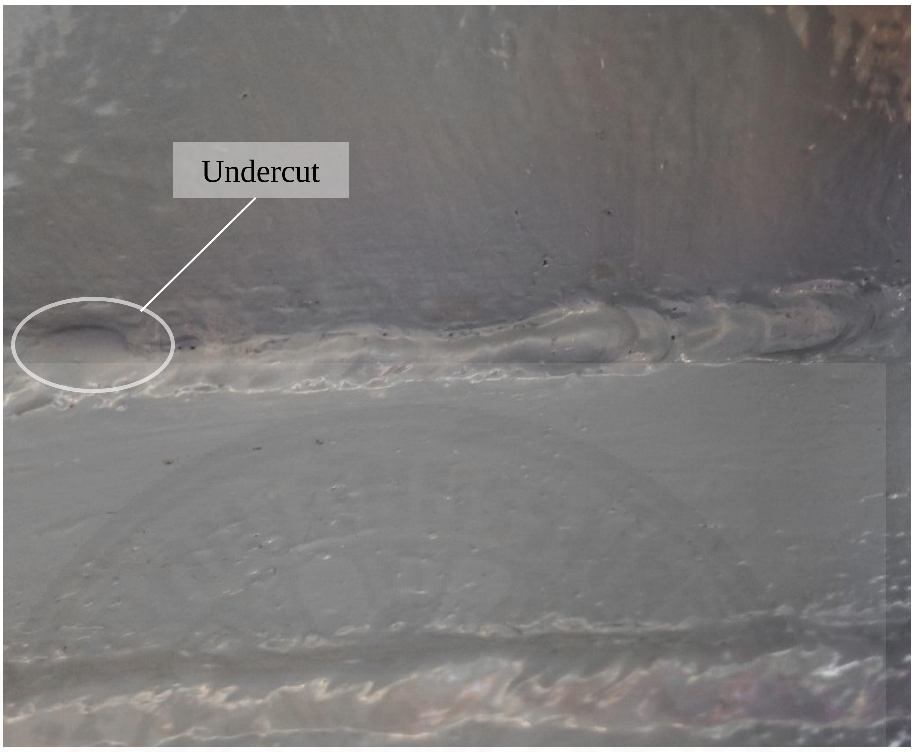


Fig 4.94 Welding defects on Steel Structure A (joint 1)

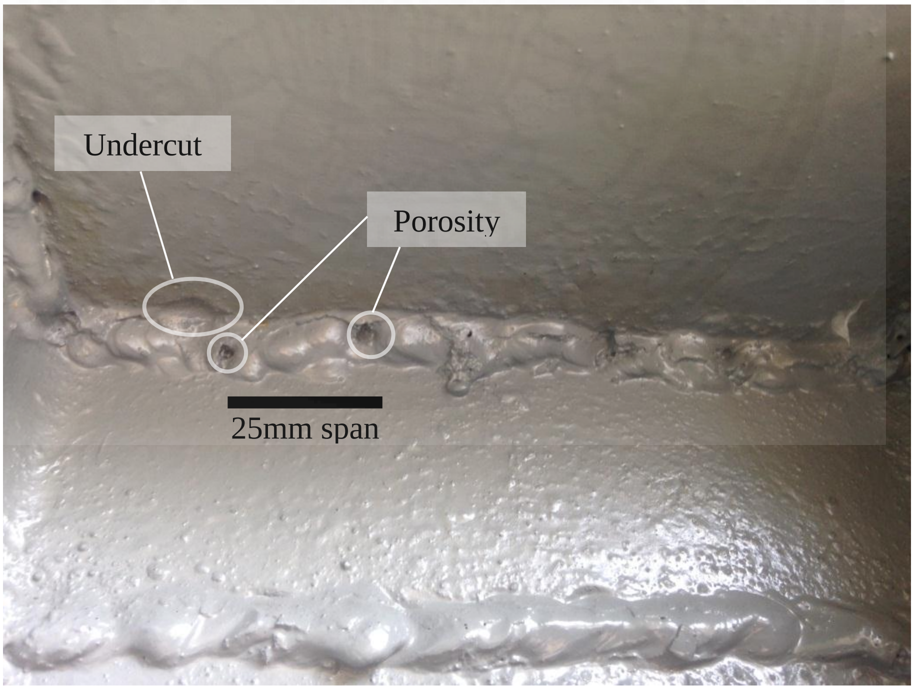


Fig 4.95 Welding defects on Steel Structure A (joint 2)

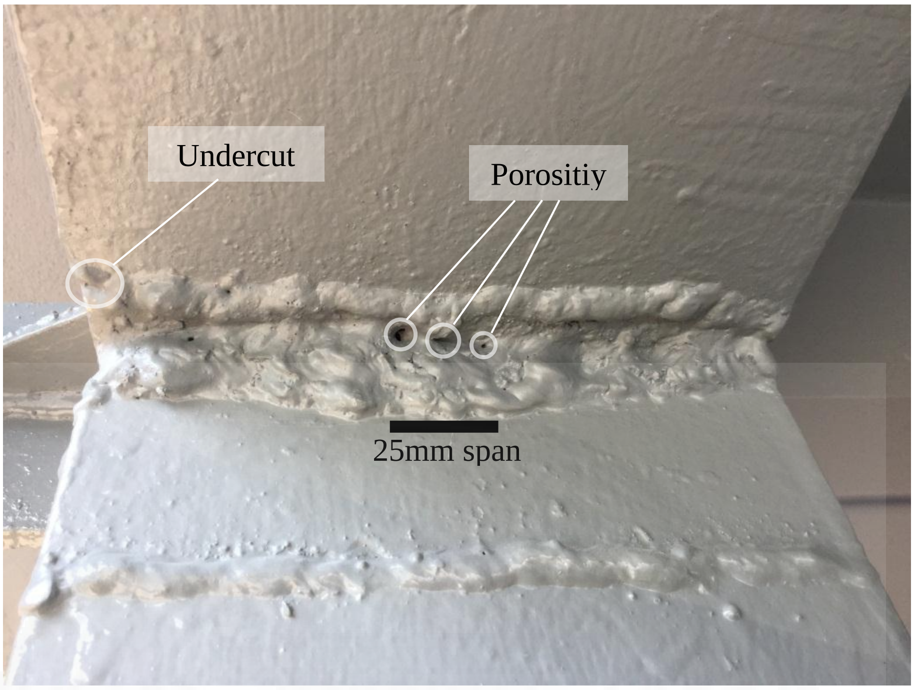


Fig 4.96 Welding defects on Steel Structure A (joint 3)

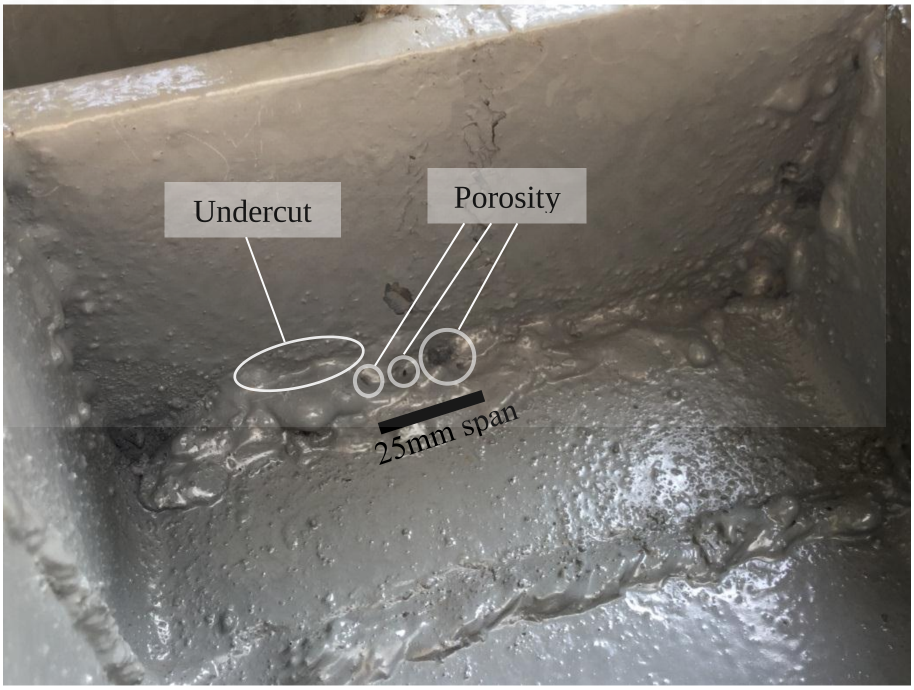


Fig 4.97 Welding defects on Steel Structure A (joint 4)

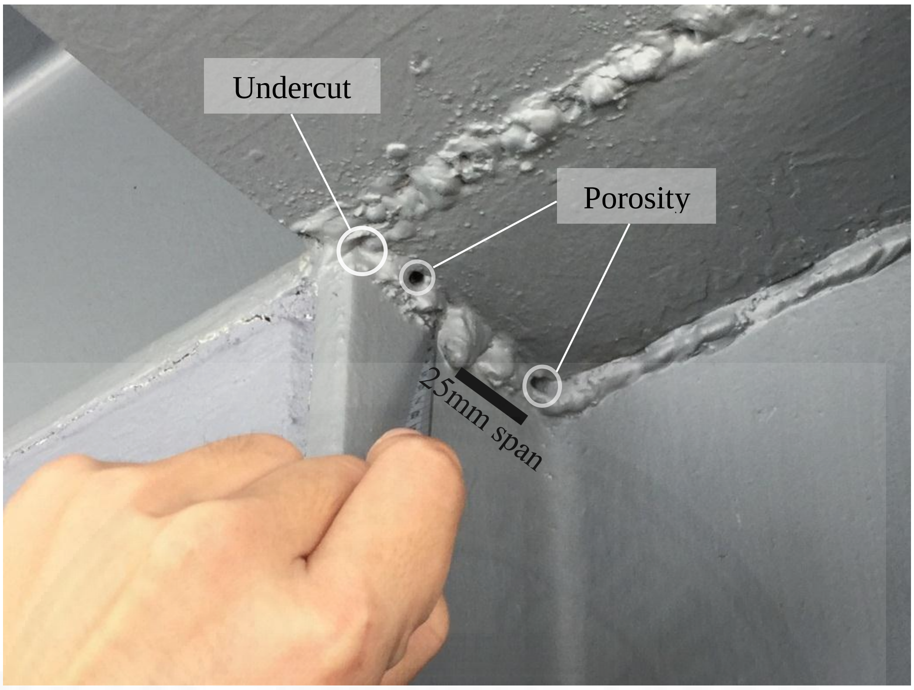


Fig 4.98 Welding defects on Steel Structure A (joint 5)

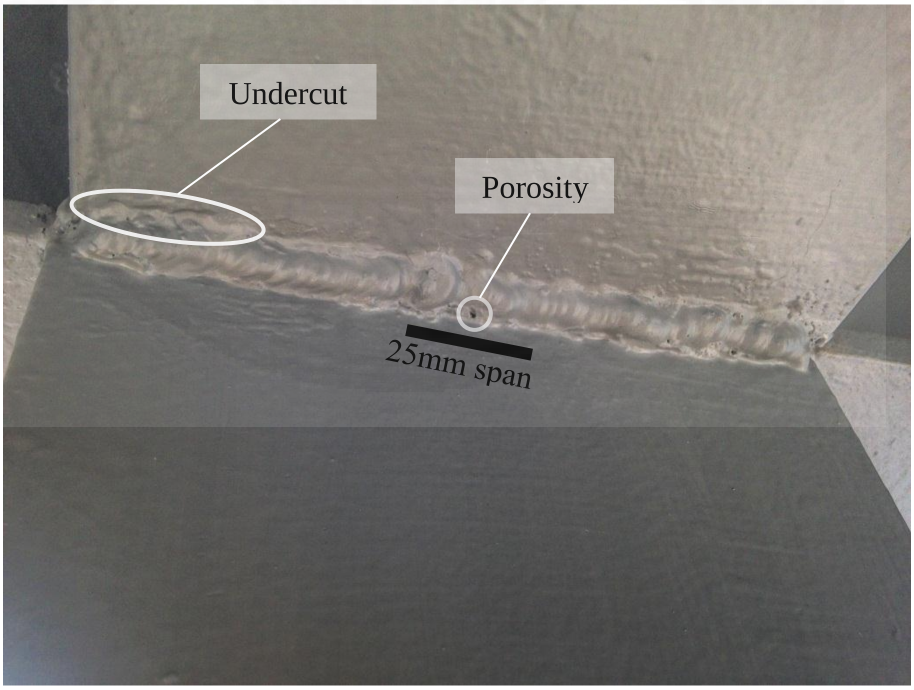


Fig 4.99 Welding defects on Steel Structure A (joint 6)

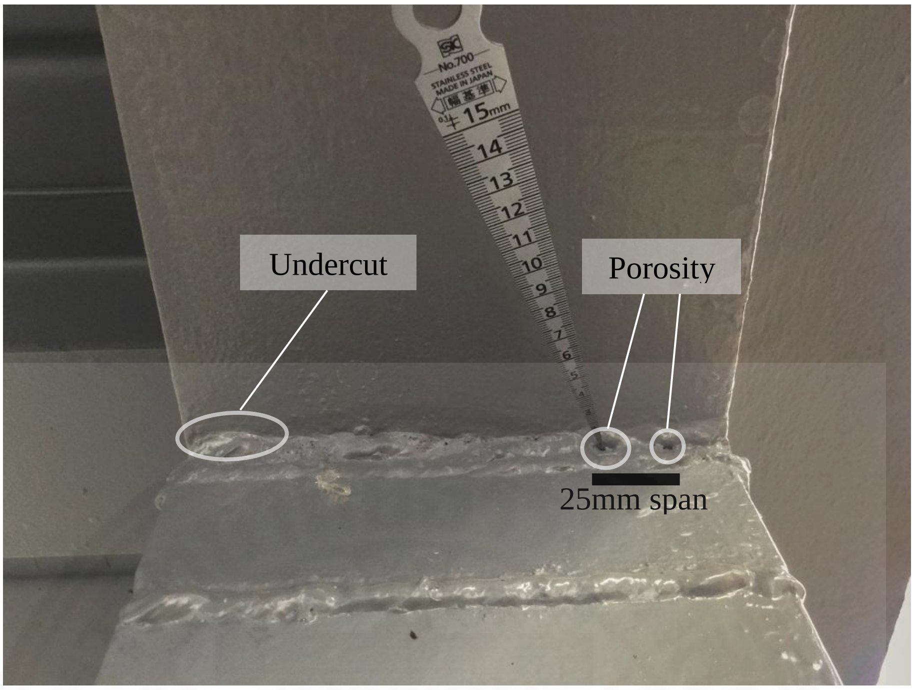


Fig 4.100 Welding defects on Steel Structure A (joint 7)

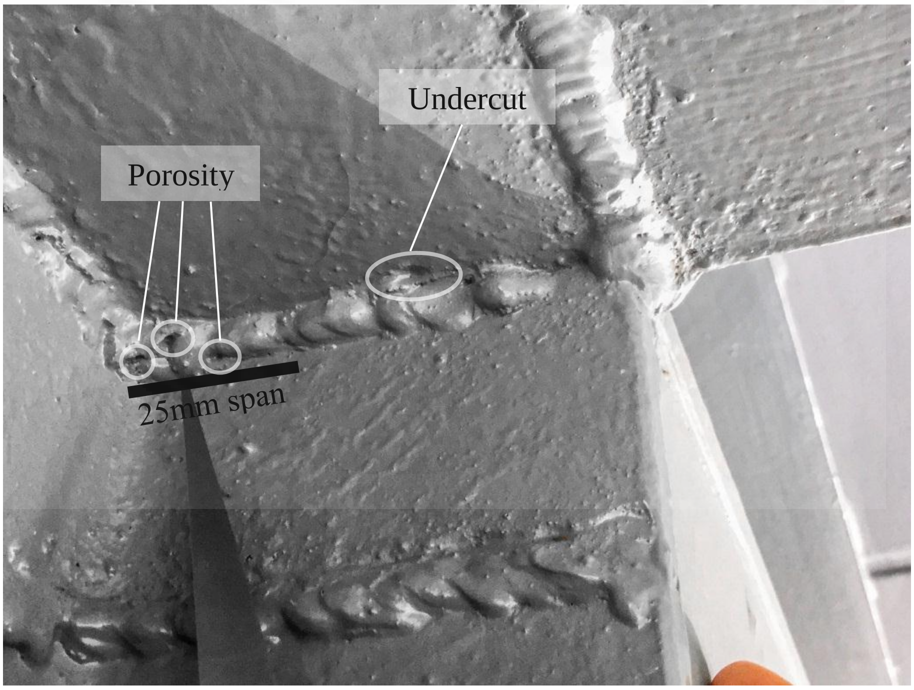


Fig 4.101 Welding defects on Steel Structure A (joint 8)

Table 4.10 Welding Inspection and Evaluation Results (Steel Structure A)

Figures	Thickness of Steel (mm)	Size of weld (mm)	Type of Weld	Defect of Weld [a]		
				Crack	Porosity [b] (mm)	Undercut [c] (mm)
Fig 4.94	10.8	150	Fillet Weld	-	-	2.1
Fig 4.95	10.8	150	Fillet Weld	-	6.0	2.7
Fig 4.96	10.8	150	Fillet Weld	-	11.0	1.0
Fig 4.97	10.8	150	Fillet Weld	-	11.1	1.0
Fig 4.98	10.8	73	Fillet Weld	-	8.0	1.5
Fig 4.99	10.8	150	Fillet Weld	-	1.0	2.2
Fig 4.100	10.8	150	Fillet Weld	-	8.0	2.4
Fig 4.101	10.8	73	Fillet Weld	-	7.0	2.7

[a] Shaded area means "Unacceptable" according to DPT 1561-51

[b] Values specified in this column is the sum of diameter of the porosity/inch (25mm)

[c] Values specified in this column is the maximum depth of undercut

Discussion

Since this structure was recently built and doesn’t locate in severe environment, so the coating of this structure is still acceptable, so the inspections were focused only on to beam-column welded connection.

From the inspection results, it can be conclude that the defect of the welding came from poor workmanship, because all of these defects occurred since the welding procedure, so it shows that this site didn’t done any welding inspection following Thailand standard. The defects found in this inspection affect the capacities to be decrease causing some risk for the structure failure.

4.1.4.4 Steel Low-Rise Building B (Steel Structure B)

Steel Structure B was built in 2005 by welded connection, and was coated by paint on the steel surface, the building was located in the middle of Thailand near the main road, the steel structure that was inspected were in front of the building, Fig 4.102 shows the overview structure for this building.

Fig 4.102 Structure overview of Steel Structure B

Maintenance Personnel Interview

This structure was private properties and was left empty since it was built, so the interview data cannot be obtain for this site.

Steel Surface Inspection and Evaluation Results

The steel surface inspection shows no damage or defect on the steel coating, since this structure was located in the city area. Also, the structure was exposed to only some pollution and rain.

Steel Connection Inspection and Evaluation Results

Steel Structure B was thoroughly inspected base on DPT 1561-51 visual inspection criteria and evaluated based on each type of welding defects similarly to the billboard inspection.

The inspection results show many weld defects mainly undercuts at the welding, the results was recorded in the form of table (Table 4.11), which shows the size of the defect (depth and diameter) on each welds in relation with the figures of each joint, as in the figure shows the location of defect (see Fig 4.103 to Fig 4.109).

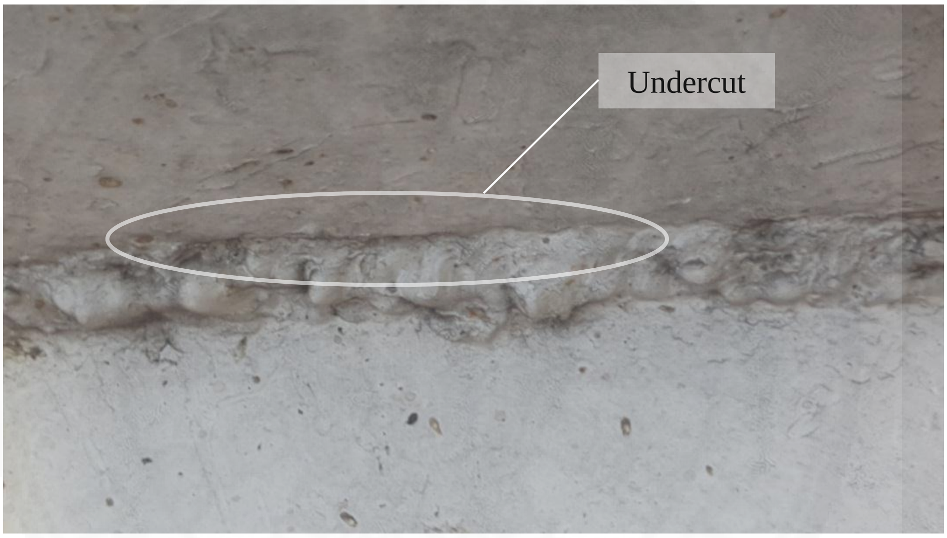


Fig 4.103 Welding defects on Steel Structure B (joint 1)

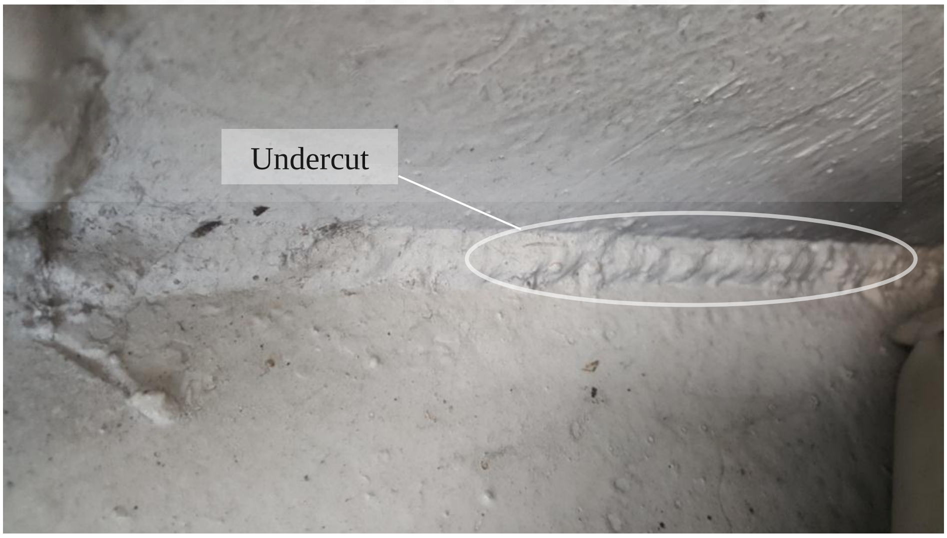


Fig 4.104 Welding defects on Steel Structure B (joint 2)

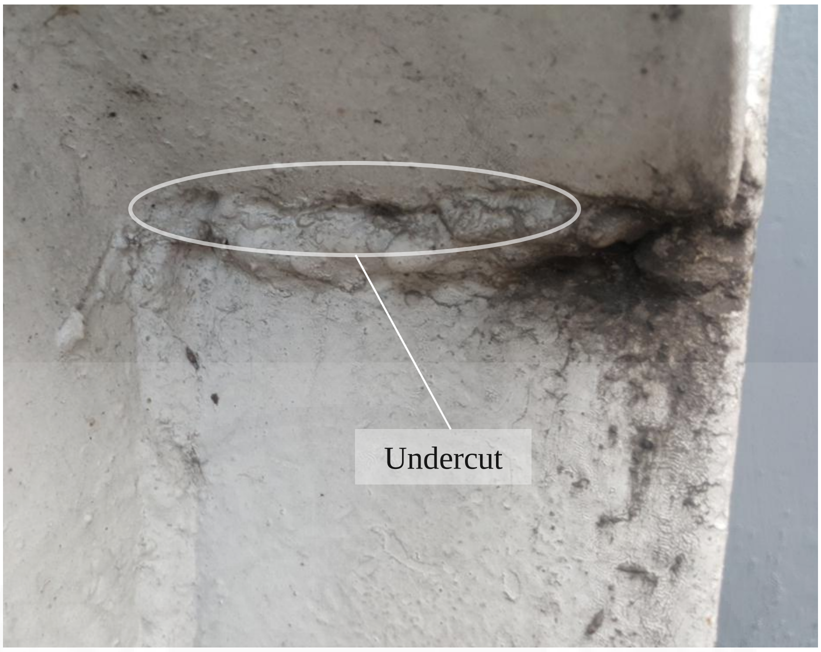


Fig 4.105 Welding defects on Steel Structure B (joint 3)

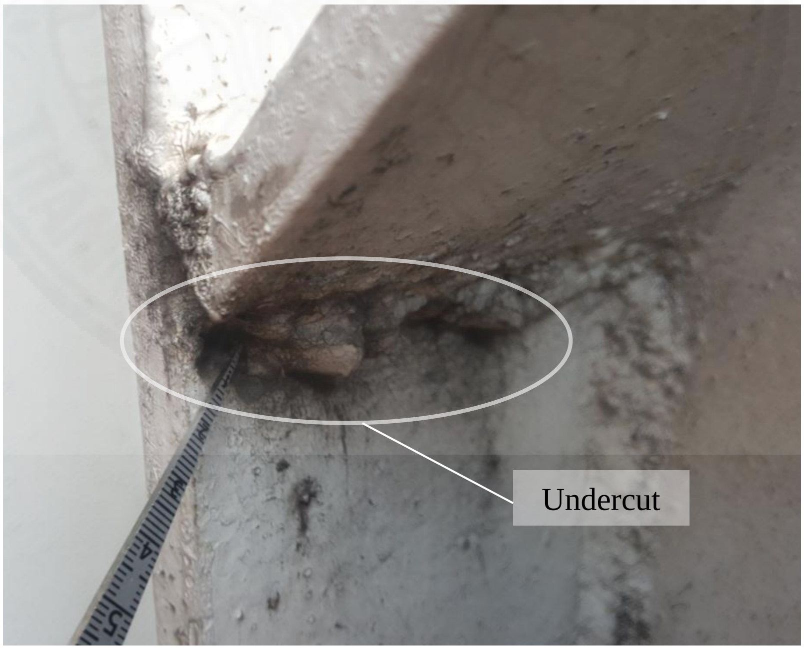


Fig 4.106 Welding defects on Steel Structure B (joint 4)

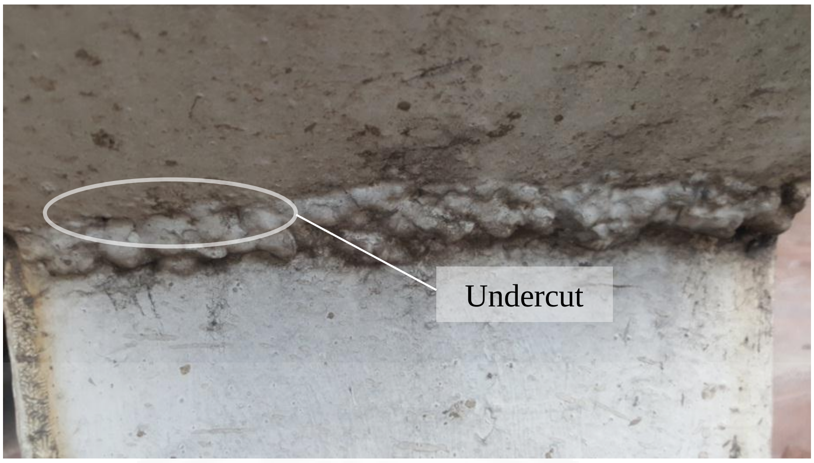


Fig 4.107 Welding defects on Steel Structure B (joint 5)

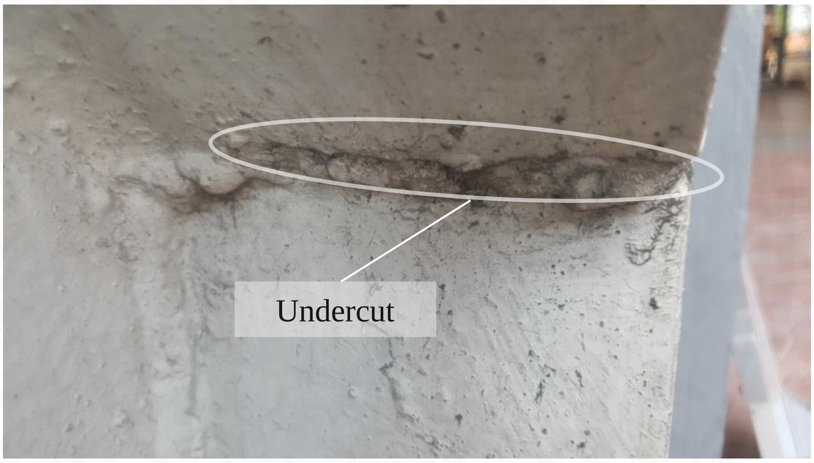


Fig 4.108 Welding defects on Steel Structure B (joint 6)

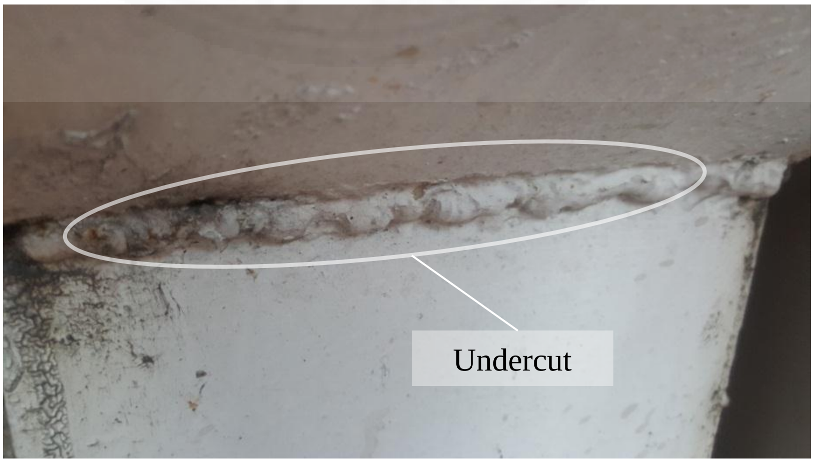


Fig 4.109 Welding defects on Steel Structure B (joint 7)

Table 4.11 Welding Inspection and Evaluation Results (Steel Structure B)

Figures	**Thickness of Steel (mm)**	**Size of weld (mm)**	**Type of Weld**	**Defect of Weld [a]**		
				Crack	**Porosity [b] (mm)**	**Undercut [c] (mm)**
Fig 4.103	10.8	150	Fillet Weld	-	-	1.0
Fig 4.104	10.8	150	Fillet Weld	-	-	0.5
Fig 4.105	10.8	150	Fillet Weld	-	-	1.7
Fig 4.106	10.8	150	Fillet Weld	-	-	2.8
Fig 4.107	10.8	150	Fillet Weld	-	-	1.1
Fig 4.108	10.8	150	Fillet Weld	-	-	1.5
Fig 4.109	10.8	150	Fillet Weld	-	-	1.7

[a] Shaded area means "Unacceptable" according to DPT 1561-51

[b] Values specified in this column is the sum of diameter of the porosity/inch (25mm)

[c] Values specified in this column is the maximum depth of undercut

Discussion

Because this structure was doesn't locate in severe environment, so the coating of this structure is still acceptable, so the inspections were focused only on to beam-column welded connection.

From the inspection results, it can be conclude that the defect of the welding came from poor workmanship, because all of these defects occurred since the welding procedure, so it shows that this site didn't done any welding inspection following Thailand standard. In addition, undercut occurred from the weld process will affect the capacities of this structure to be decrease, and caused some risk for the structure failure.

4.2 Proposed countermeasure

The proposed countermeasures were divided into three phases consist of; 1) Design phase, 2) Construction phase, 3) Maintenance phase.

4.2.1 Design phase

Design phase is to control the quality of the steel product for the design process. Steel products or materials used in Thailand could manufacture from many firms, both domestic and foreign factory. With different production process, the properties of the product could be different. To ensure that the material from different sources can be used in construction safely and correctly, a classification of steel material should be applied. The classification of steel material might base on adequacy assessment, the overall framework shown in Fig 4.110. The classification might certify the steel material into three different classes (Class 1, Class 2, and Class 3). The design approaches are different based on this classification (BC1: 2012).

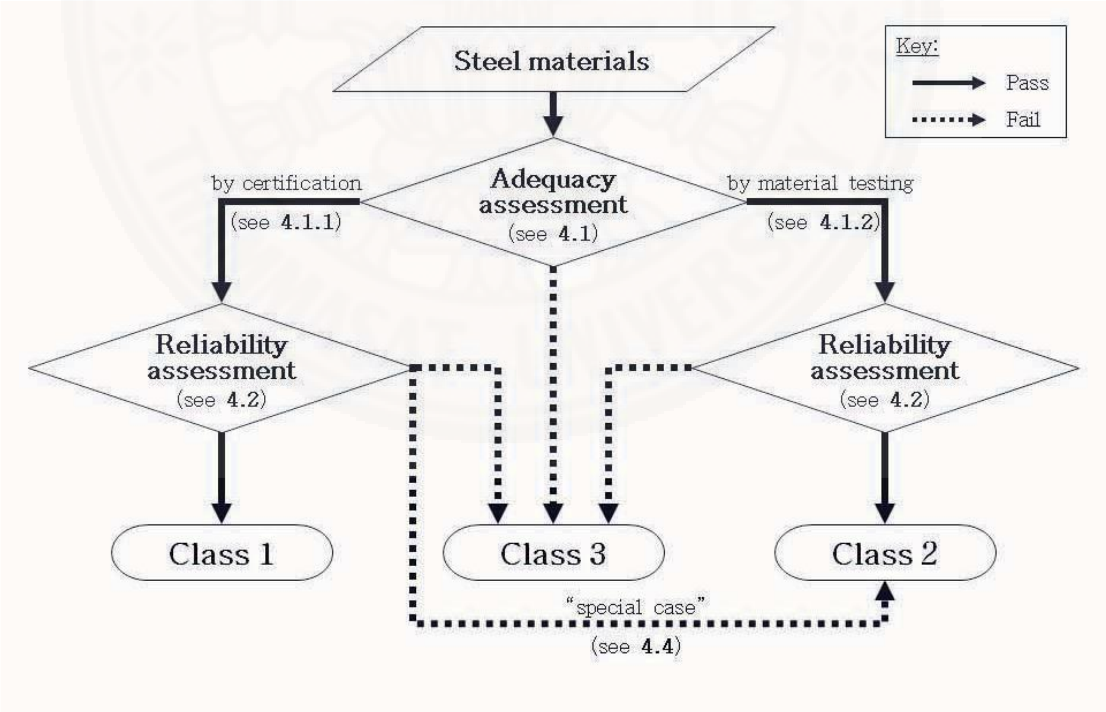


Fig 4.110 Overall framework for classification of steel materials

(Reference: BC1: 2012, Page 21. Figure 1)

For Class 1 materials, the materials have to pass the certification process of verification of the steel material properties against the material performance requirements. The verification was done based on well-known material specification standards from different countries, such as British/European, American, Japanese, Australian/New Zealand, and Chinese material standards. And for Class 2 material, the material has to pass the material testing to verify the material performance requirements. The material performance requirements consist of the steel specific properties in relation with the types of the steel sections (shown in Table 4.12).

Table 4.12 Material performance requirements (BC1: 2012)

Type of steel materials	Specific Properties
• Steel plates • Hot rolled sections • hollow section • Steel for cold forming	• Yield strength • Tensile strength • Elongation after facture • Impact energy • Chemical content • Carbon equivalent value
• Non-preloaded bolting assemblies • Preloaded bolting assemblies	• Yield strength (bolts) • Tensile strength (bolts) • Elongation after facture (bolts) • Hardness (bolts, nuts and washers) • Proof load stress (nuts) • Chemical content
• Welding consumables	• Yield strength • Tensile strength • Elongation after facture • Impact energy
• Profiled steel sheets	• Yield strength • Tensile strength • Chemical content
• Stud shear connectors	• Yield strength • Tensile strength • Elongation after facture

For Class 3 materials, the materials in this class do not meet any requirements and should be used carefully.

As mentioned previously, that the design approaches are different based on the classification of steel material. For Class 1 materials, the design parameter should be up to 100% of its original capacity. For example, in BC1: 2012 specified the design parameter of a material, manufactured under Japanese standard to be the same as its original strength, as shown in Table 4.13 (BC1: 2012).

Table 4.13 Design parameters of Japanese (JIS) structural steels (BC1: 2012)

Grade	p_y or f_y (N/mm^2), for thickness (mm) less than or equal to					
	16	40	75	100	160	200
400	245	235	215	215	205	195
490	325	315	295	295	285	275
490Y	365	355	335	325	-	-
520	365	355	335	325	-	-
570	460	450	430	420	-	-

For Class 2 material, the design parameter should be up to 95% of its original capacity. For example, in BC1: 2012 specified the design parameter of a Class 2 material, as shown in Table 4.14 (BC1: 2012), the design parameter vary around 95% to 80%.

Table 4.14 Design parameters of Class 2 structural steels (BC1: 2012)

Basic design parameters for thickness[a] less than or equal to 16 mm	Design parameters for thickness[a] (mm) less than or equal to				
	40	63	80	100	150
$p_{yo} = \frac{Y_s}{1.1} \le \frac{U_s}{1.3}$ or 460 N/mm^2	$p_y = 0.95p_{yo}$	$p_y = 0.92p_{yo}$	$p_y = 0.90p_{yo}$	$p_y = 0.85p_{yo}$	$p_y = 0.80p_{yo}$
$f_{yo} = \frac{R_{eh}}{1.1} \le \frac{R_m}{1.3}$ or 460 N/mm^2	$f_y = 0.95f_{yo}$	$f_y = 0.92f_{yo}$	$f_y = 0.90f_{yo}$	$f_y = 0.85f_{yo}$	$f_y = 0.80f_{yo}$
a For rolled sections, used the specified thickness of the thickest element of the cross-section.					

For Class 3 material, the design parameter should be limited up to a certain level. For example, in BC1: 2012 specified the design parameter of a Class 2 material, as shown in Table 4.15 (BC1: 2012), the design parameter only up to 170 N/mm^2.

Table 4.15 Design parameters of Class 3 structural steels (BC1: 2012)

p_y or f_y (N/mm^2), for thickness[a] (mm) less than or equal to					
16	**40**	**63**	**80**	**100**	**150**
170	160	155	150	145	135
a For rolled sections, used the specified thickness of the thickest element of the cross-section.					

4.2.2 Construction phase

The construction phase involved with preventing the damage from the defect during the construction process, which could cause severe damage to the structure in the future. The main target of this phase is to decrease poor construction methods and poor workmanship. This phase is consist of; 1) Construction Handbook, 2) Accreditation Systems.

4.2.2.1 Construction handbook

The construction handbook might specify a construction methods and workmanship specification, in order to improve the quality of the construction works. Also, it might relate to the inspection and evaluation routine in the next section. Further, the handbook should specify the specification of welding, fabricating, installing, and assembling the steel structure. For example, the shop drawing should be made accurately according to design specification in the design documents, and should be approved by the engineer (JASS6, 1993). Or, for the assembly of steel connection, special attention should be paid to achieve a tight fit of the joint parts. Distortion, warping and bending in the joint part of the connected member, and bending of the splice plate, etc. should be corrected with care taken not to damage the friction surface (JASS 6, 1993).

4.2.2.2 Accreditation of fabricators and welders

Quality control of the steel work is possibly another issue in Thailand, as show in the research that the welding work was done poorly in many steel structures. The countermeasure against this issue is to establish the accreditation of fabricators and welders to control the quality of the steel work. Additionally, the accreditation shall divided into several levels or types, to indicate the work that a certain firm or welder could do. For example, the structural steel fabricators accreditation of

Singapore were divided into four categories, as Category S1 to Category S4 based on the infrastructure, resources and capabilities to fabricate and erect structural steel structures of that firm. For example, the firm that has building of over 30 m in height, or large span bridges of over 30 m will be classified as Category S1, or up to 30 m will be classified as Category S2, or up to 20 m will be classified as Category S3, and finally up to 10 m will be classified as Category S4 (Reference: Structural steel fabricators accreditation of Singapore).

4.2.3 Maintenance phase

Maintenance phase is to draft a Standard and Guideline for Inspection and Maintenance. Standard and guideline is essential in order to conduct a proper inspection and maintenance on existing steel structures. The proposed countermeasure is to draft a standard and guideline for inspection and maintenance, which might include three parts; 1) inspection criteria, 2) Evaluation criteria and Classification of severity (damage rating), 3) Repair and protection options.

For the first part, the standard should specify the inspection criteria divided base on types of damage and defect. For example, undercut should be visually inspected by using welding gauge to measure its depth, and if the depth exceeds the limit of 1.0 mm, the weld might be considered as “Unacceptable” and should be repair. Additionally, for some specific types of welding defect might inspect by using the other NDT method. For example, crack on the surface of the weld might use MT or PT to inspection the propagation of crack on the weld surface, since crack on the weld surface is too small to see with bare eyes (DPT 1561-51 to 1565-51).

For the second part, the evaluation criteria should be performed base on the severity of damage. For example, rusting damage might be rated as “degree of rusting” from level 1 to 5 according to the severity of damage. Additionally, the rating scheme might specify with the repairing methods for each level of damage. This rating scheme might result in proper countermeasures (ISO 4628-3).

For the third part, the repair and protection options should specify the repairing methods and repairing materials. In addition, the repairing methods should base on the severity of the damage, and type of damage from the inspection and evaluation. For example, for minor corrosion damage (no sectional area lost) or the deterioration of paint, the repairing method might be done by removing the paint and corrosion of the steel surface, then repaint with an anti-corrosive paint. For a major corrosion damage (sectional area lost), the repairing method might be done by replace the corroded steel section with the new section, and then protected by using anti-corrosive paint. Additionally, steel must be prepared and clean before painting, to ensure the quality of the protection. Also, the moisture level during the painting process shall be concerned, since high humidity environment might cause a blistering under the paint. Further, if the damage or defect due to welding process such as crack and porosity, this can be repair by using grinning/gouging out the defective area and re-welding. Also, undercut can be repaired by welding up the resultant groove with the smaller electrode (Baughurst, L., Voznaks, G.,2009).

Finally, guidelines should specify the inspection routines, scope of inspections, inspection checklists, evaluation references, repairing procedures for each type and level of damage, as well as frequency of inspections. For example, steel power plant should have an inspection routine every 2 years; the inspection area should consist of Steel Surface inspection and Steel connection inspection. Furthermore, steel connection should be inspection thoroughly, especially at the sensitive area of the structure, i.e. moment connection and shear connection. In addition, if the power plant located in heavy environmental area, the frequency of inspections might increase up to every 1 year or higher.

Chapter 5
Conclusion

5.1 Conclusion

In conclusion, the majority of damage or defect on the existing steel structures in Thailand was divided into two types, which are the damage during construction process and the damage after construction.

For the first type of damage, the damage from the defects, caused from poor workmanship in the construction process could leads to structural failure, because structural defects could result in decreasing of structural capacity directly. For instance, the defect caused by welding processes result in the decreasing of the strength of welds. While, in a good fabrication factory contains better quality control system to ensure the quality of their work. However, these defects can be fixed directly by redoing the construction process, such as re-weld, re-paint, and re-install. Furthermore, the defect from poor painting workmanship could create a severe damage to the structure, like in the case of Power Plant B, which the unpainted area near the connection turns into severe corrosion damage. Although, the workmanship can never be perfect, since there is a difficult in the work process, such as the position of the welds (over-head welding position in practice is very difficult) so the welding product will never be as good as the welds produce by normal welding position or the inaccessible surface is hard to accessed and painted properly. Also, a good maintenance quality will never be achieve without times and skilled labors.

For the second type of damage, the damage that occurred after construction or that occurred during the service life of the structure, which are the damage from the deterioration of the steel coating caused by the surrounding environment. Furthermore, the deterioration of steel coating can leads to the corrosion damage on the steel surface. However, damage caused by the environment can be solved by a good maintenance and good protection. Additionally, maintenance routine could include inspection and evaluation, since these processes is essential for the maintenance personnel to be able to acknowledge the status of such structure.

The inspection results show that, the majority of steel structure in Thailand tends to have a lot of corrosion damage, especially the steel structure that was located in heavy environmental area. For example, the power plant in the north of Thailand has less corrosion damage than the power plant in the south of Thailand which located near the sea. However, despite the environmental difference, the other factor which can control the severity of the damage is the frequency of maintenance routine. For instance, Both Power Plant B and Power Plant D were located near the estuary, but Power Plant B tends to have more severe corrosion damage than Power Plant D, since Power Plant D has better maintenance system than Power Plant B.

Finally, the proposed countermeasures in this research were divided into three phases, which are design phase, construction phase, and maintenance phase. Firstly, the overall objective of the design phase was to control the quality of the steel materials that was manufactured from the different places. Since, there are a lot of problems about the quality of the material which were imported from foreign countries especially from China. The design phase might be able to control the use of those materials, by controlling the design parameters. Secondly, the construction phase was mainly emphasized on the quality control of the construction work. The construction handbook mainly proposed the correct construction methods, in order to achieve a good quality of the construction works. And, the accreditation of fabrication was mainly to control the work produced by different fabricator. Furthermore, to prevent the fabricator to produce the work that exceed there capability. Lastly, the maintenance phase was mainly emphasized on drafting a standards and guidelines for inspection and evaluation of steel structures, to improve the quality of the maintenance works for the durable steel structure. The standard and guideline consist of inspection criteria, evaluation criteria and classification of severity (damage rating), and repair and protection options.

5.2 Recommendation of Further work

Further work recommendation for this research would inspect the existing steel structure practically by using the other Non-destructive testing methods such as Liquid penetrant testing (PT), Magnetic particle testing (MT), and Ultrasonic testing (UT). Also, in further work shall expend the target structure to cover a wider scope, such as steel factory, and steel railway bridge.

References

AISC 360-10. Specification for Structural Steel Buildings. *American Institute of Steel Construction*, United State of American, 2010.

ASTM D610 – 1. Standard Testing Method for Evaluating Degree of Rusting on Painted Steel Surfaces. ASTM International, West Conshohocken, United States, 2001.

ASTM D714 – 2. Standard Test Method for Evaluating Degree of Blistering on Painted Steel Surfaces. ASTM International, West Conshohocken, United States, 2009.

AWS D1.1/D1.1M. Structural Welding Code – Steel. *American Welding Society,* Miami, FL 33126, 2010.

Baughurst, L., Voznaks, G. (2009). Welding defects, causes and corrosion. *Australian Bulk Handling Review: July/August 2009,* 26-28.

BC1: 2012. Design Guide on Use of Alternative Structural Steel to BS 5950 and Eurocode 3. *Building and Construction Authority*, Singapore, 2012.

DPT 1561 – 51 To 1565 – 51. Structural Steel welding inspection standard. *Department of Public Works and Town & Country Palnning*, Thailand, 2008.

Fontana, M. (Ed). (1986). *Corrosion Engineering*. New York: McGraw-Hill.

ISO 4628 – 1. Paints and Varnishes – Evaluation of degree of coatings –designation of quantity and size of defect, and of intensity of uniform changes in appearance – Part 1: General introduction and designation system. *International Standard Organization,* Switzerland, 2003.

ISO 4628 – 2. Paints and Varnishes – Evaluation of degree of coatings –designation of quantity and size of defect, and of intensity of uniform changes in appearance – Part 2: Assessment of degree of blistering. *International Standard Organization,* Switzerland, 2003.

ISO 4628 – 3. Paints and Varnishes – Evaluation of degree of coatings –designation of quantity and size of defect, and of intensity of uniform changes in appearance – Part 3: Assessment of degree of rusting. *International Standard Organization,* Switzerland, 2003.

ISO 4628 – 4. Paints and Varnishes – Evaluation of degree of coatings –designation of quantity and size of defect, and of intensity of uniform changes in appearance – Part 4: Assessment of degree of cracking. *International Standard Organization,* Switzerland, 2003.

ISO 4628 – 5. Paints and Varnishes – Evaluation of degree of coatings –designation of quantity and size of defect, and of intensity of uniform changes in appearance – Part 5: Assessment of degree of flaking. *International Standard Organization,* Switzerland, 2003.

JASS 6. Japanese Architectural Standard Specification JASS 6 (1993) Structural Steelwork Specification for Building Construction. *Architectural Institute of Japan*, Japan, 1993.

JIS B 1186. Set of high strength hexagon bolt, hexagon nut and plain washers for friction grip joints. *Japanese Industrial Standard,* Japan, 1995.

RCSC. Specification for Structural Joints Using High – Strength Bolts. *Research Council in Structural Connections,* Chicago, Illinois, 2009.

Structural Steel Fabricators Accreditation Scheme. Singapore Structural Steel Society (SSSS), Singapore, 13 Mar, 2014.

TIS 2387- 2555. Industrial Standards for Anticorrosive priming paint. *Thailand Industrial Standard,* Thailand, 2012.

Appendices

Appendix A

Welding Visual Inspection Criteria

Table 6.1
Visual Inspection Acceptance Criteria (see 6.9)

Discontinuity Category and Inspection Criteria	Statically Loaded Nontubular Connections	Cyclically Loaded Nontubular Connections	Tubular Connections (All Loads)
(1) Crack Prohibition Any crack shall be unacceptable, regardless of size or location.	X	X	X
(2) Weld/Base-Metal Fusion Complete fusion shall exist between adjacent layers of weld metal and between weld metal and base metal.	X	X	X
(3) Crater Cross Section All craters shall be filled to provide the specified weld size, except for the ends of intermittent fillet welds outside of their effective length.	X	X	X
(4) Weld Profiles Weld profiles shall be in conformance with 5.24.	X	X	X
(5) Time of Inspection Visual inspection of welds in all steels may begin immediately after the completed welds have cooled to ambient temperature. Acceptance criteria for ASTM A 514, A 517, and A 709 Grade 100 and 100 W steels shall be based on visual inspection performed not less than 48 hours after completion of the weld.	X	X	X
(6) Undersized Welds The size of a fillet weld in any continuous weld may be less than the specified nominal size (L) without correction by the following amounts (U): L, specified nominal weld size, in [mm] — U, allowable decrease from L, in [mm] ≤ 3/16 [5] — ≤ 1/16 [2] 1/4 [6] — ≤ 3/32 [2.5] ≥ 5/16 [8] — ≤ 1/8 [3] In all cases, the undersize portion of the weld shall not exceed 10% of the weld length. On web-to-flange welds on girders, underrun shall be prohibited at the ends for a length equal to twice the width of the flange.	X	X	X
(7) Undercut (A) For material less than 1 in [25 mm] thick, undercut shall not exceed 1/32 in [1 mm], with the following exception: undercut shall not exceed 1/16 in [2 mm] for any accumulated length up to 2 in [50 mm] in any 12 in [300 mm]. For material equal to or greater than 1 in [25 mm] thick, undercut shall not exceed 1/16 in [2 mm] for any length of weld.	X		
(B) In primary members, undercut shall be no more than 0.01 in [0.25 mm] deep when the weld is transverse to tensile stress under any design loading condition. Undercut shall be no more than 1/32 in [1 mm] deep for all other cases.		X	X
(8) Porosity (A) CJP groove welds in butt joints transverse to the direction of computed tensile stress shall have no visible piping porosity. For all other groove welds and for fillet welds, the sum of the visible piping porosity 1/32 in [1 mm] or greater in diameter shall not exceed 3/8 in [10 mm] in any linear inch of weld and shall not exceed 3/4 in [20 mm] in any 12 in [300 mm] length of weld.	X		
(B) The frequency of piping porosity in fillet welds shall not exceed one in each 4 in [100 mm] of weld length and the maximum diameter shall not exceed 3/32 in [2.5 mm]. Exception: for fillet welds connecting stiffeners to web, the sum of the diameters of piping porosity shall not exceed 3/8 in [10 mm] in any linear inch of weld and shall not exceed 3/4 in [20 mm] in any 12 in [300 mm] length of weld.		X	X
(C) CJP groove welds in butt joints transverse to the direction of computed tensile stress shall have no piping porosity. For all other groove welds, the frequency of piping porosity shall not exceed one in 4 in [100 mm] of length and the maximum diameter shall not exceed 3/32 in [2.5 mm].		X	X

Note: An "X" indicates applicability for the connection type; a shaded area indicates non-applicability.

Fig. A-1 Visual Inspection Acceptance Criteria

(Reference: AWS D1.1/D1.1M: 2010, page 239, Table 6.10)

Appendix B

Reference Photo for Paint Inspection

Figure 1 — Blisters of size 2

Fig. B-1 Blistering of size 2

(Reference: ISO 4628-2:2003, Page 3. Figure 1)

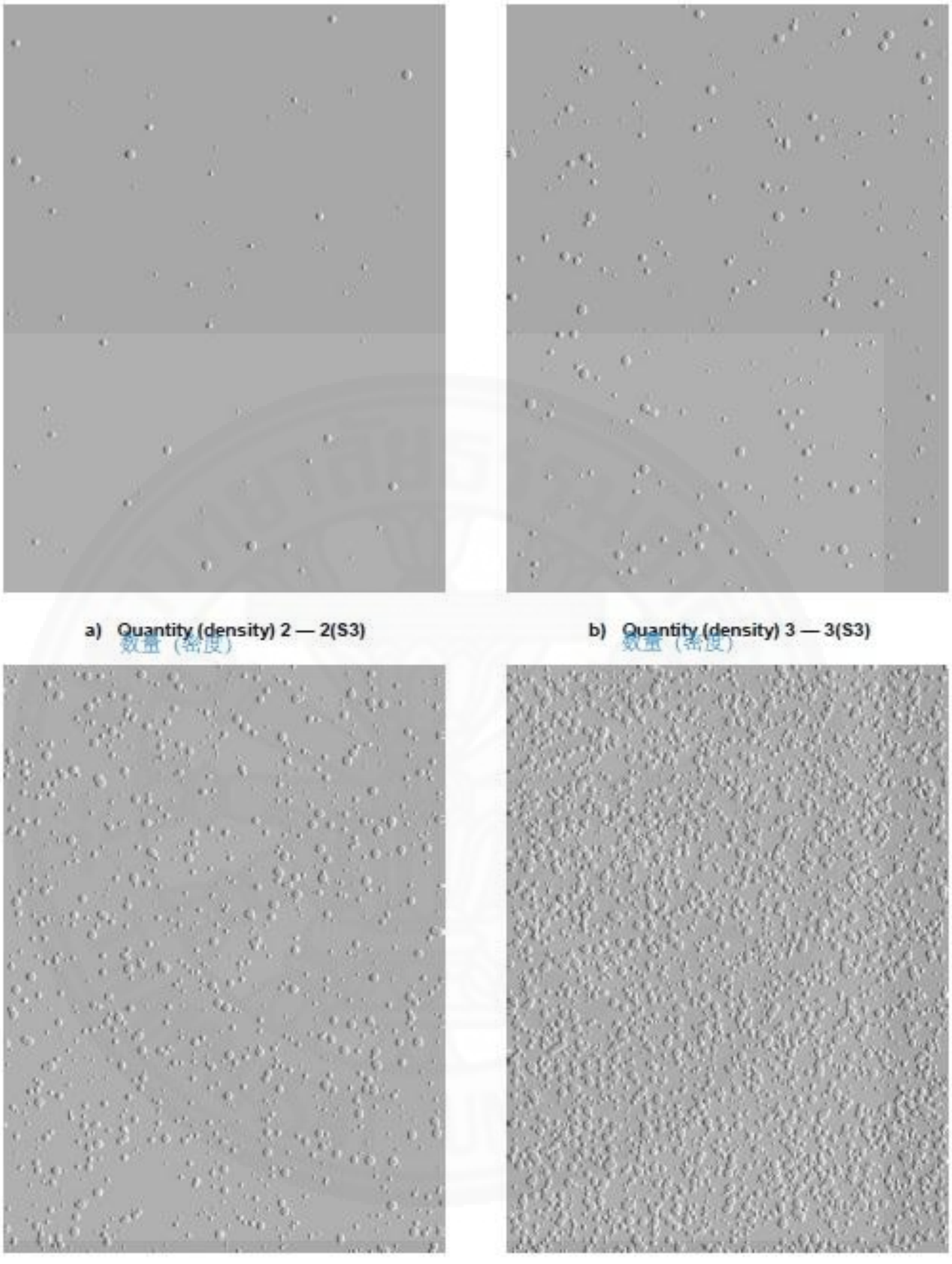
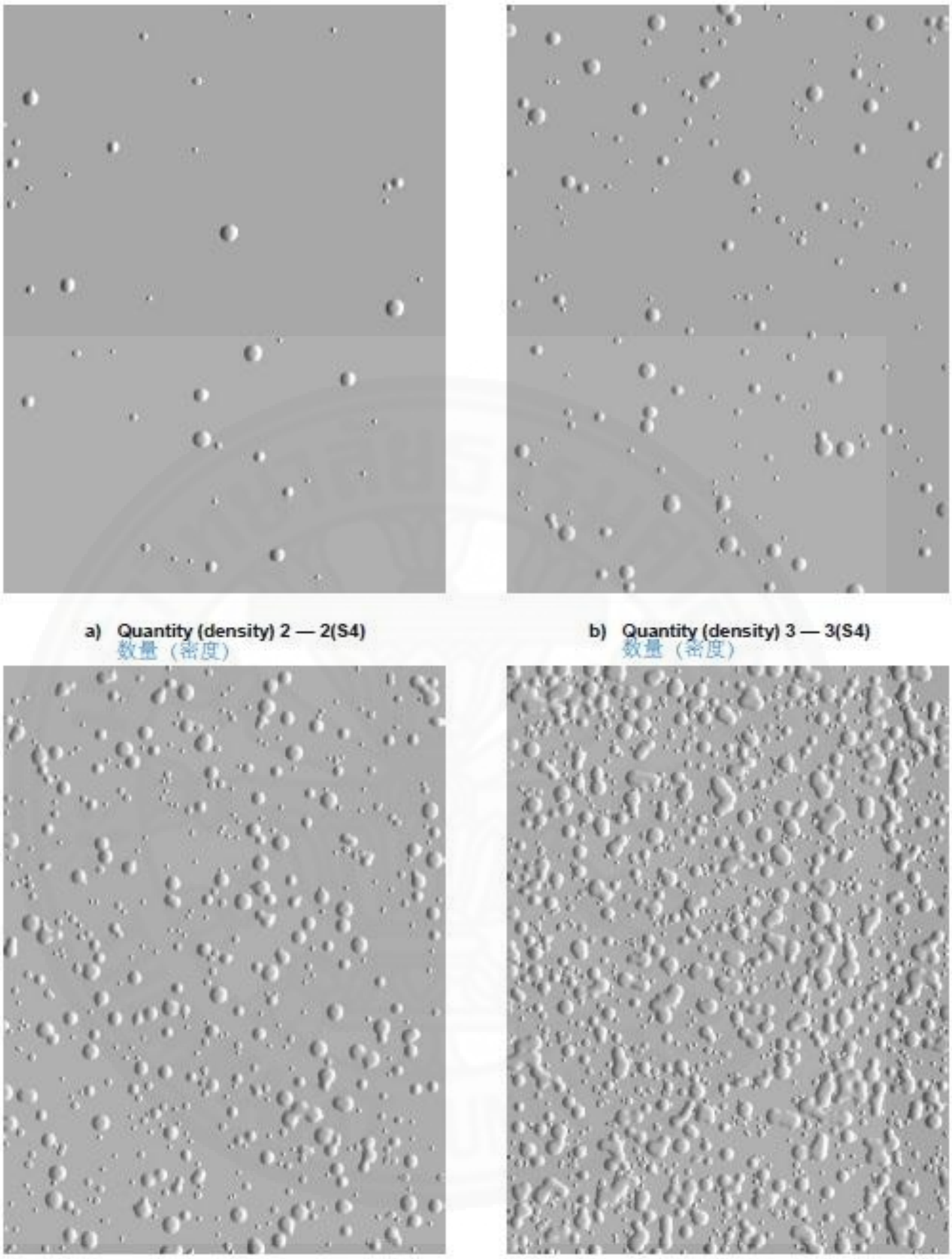


Figure 2 — Blisters of size 3

Fig. B-2 Blisters of size 3

(Reference: ISO 4628-2:2003, Page 4. Figure 2)



a) Quantity (density) 2 — 2(S4)
数量（密度）

b) Quantity (density) 3 — 3(S4)
数量（密度）

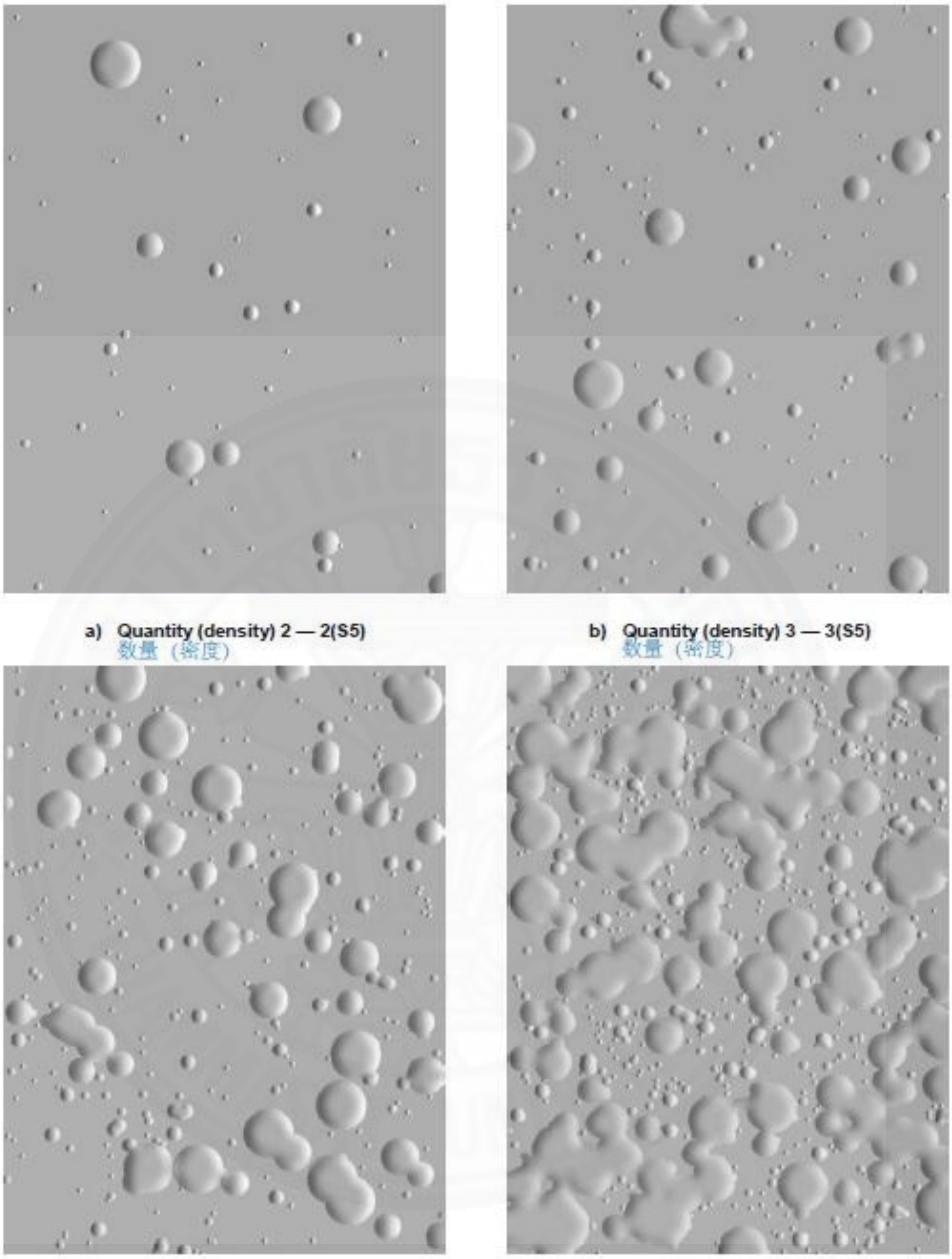
c) Quantity (density) 4 — 4(S4)
数量（密度）

d) Quantity (density) 5 — 5(S4)
数量（密度）

Figure 3 — Blisters of size 4

Fig. B-3 Blisters of size 4

(Reference: ISO 4628-2:2003, Page 5. Figure 3)



a) Quantity (density) 2 — 2(S5)
数量（密度）

b) Quantity (density) 3 — 3(S5)
数量（密度）

c) Quantity (density) 4 — 4(S5)
数量（密度）

d) Quantity (density) 5 — 5(S5)
数量（密度）

Figure 4 — Blisters of size 5

Fig. B-4 Blisters of size 5

(Reference: ISO 4628-2:2003, Page 6. Figure 4)

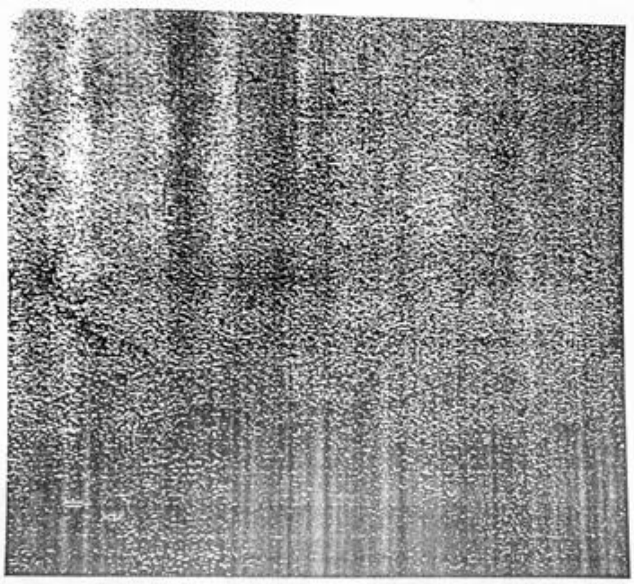


Figure 1 — Degree of rusting Ri 1

Fig. B-5 Degree of rusting Ri 1

(Reference: ISO 4628-3:2003, Page 4, Figure 1)

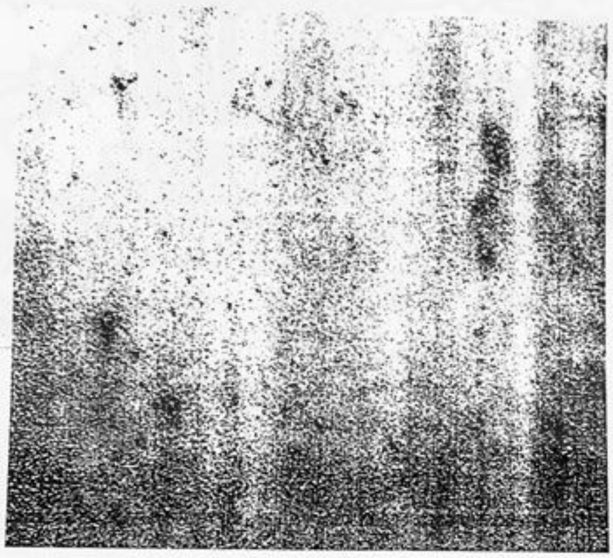


Figure 2 — Degree of rusting Ri 2

Fig. B-6 Degree of rusting Ri 2

(Reference: ISO 4628-3:2003, Page 5, Figure 2)

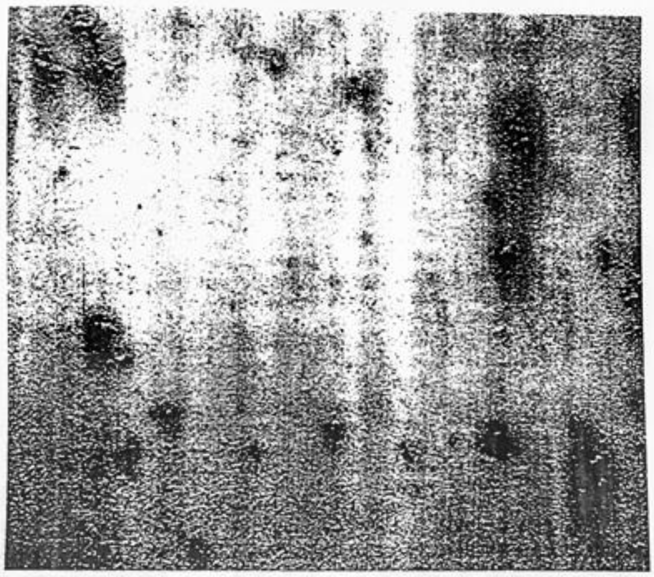


Figure 3 — Degree of rusting Ri 3

Fig. B-7 Degree of rusting Ri 3

(Reference: ISO 4628-3:2003, Page 6, Figure 3)

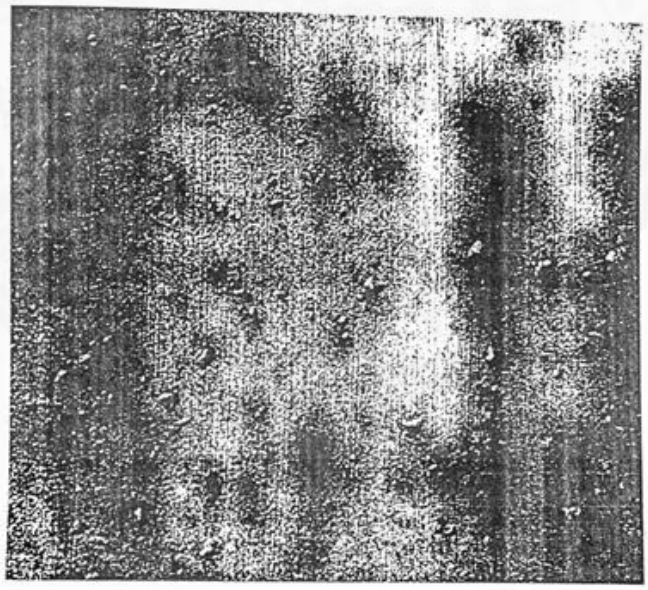


Figure 4 — Degree of rusting Ri 4

Fig. B-8 Degree of rusting Ri 4

(Reference: ISO 4628-3:2003, Page 6, Figure 4)

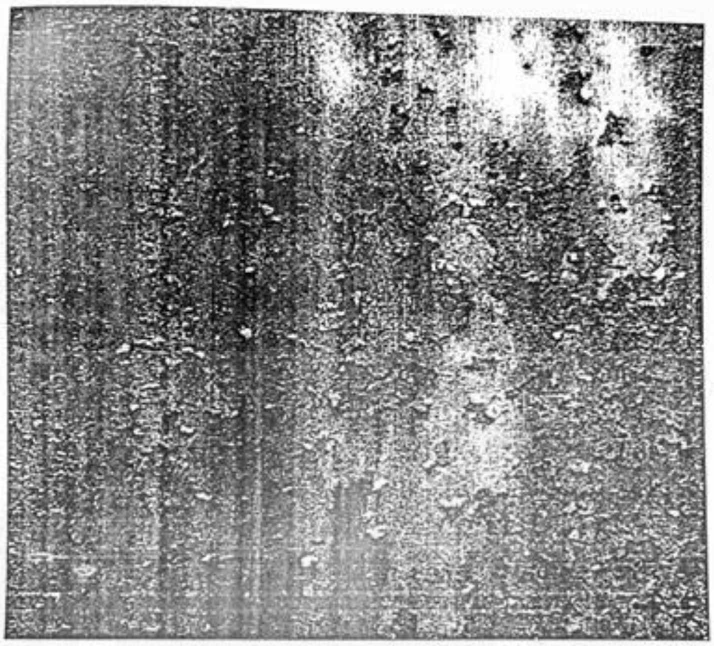


Figure 5 — Degree of rusting Ri 5

Fig. B-9 Degree of rusting Ri 5

(Reference: ISO 4628-3:2003, Page 7, Figure 5)

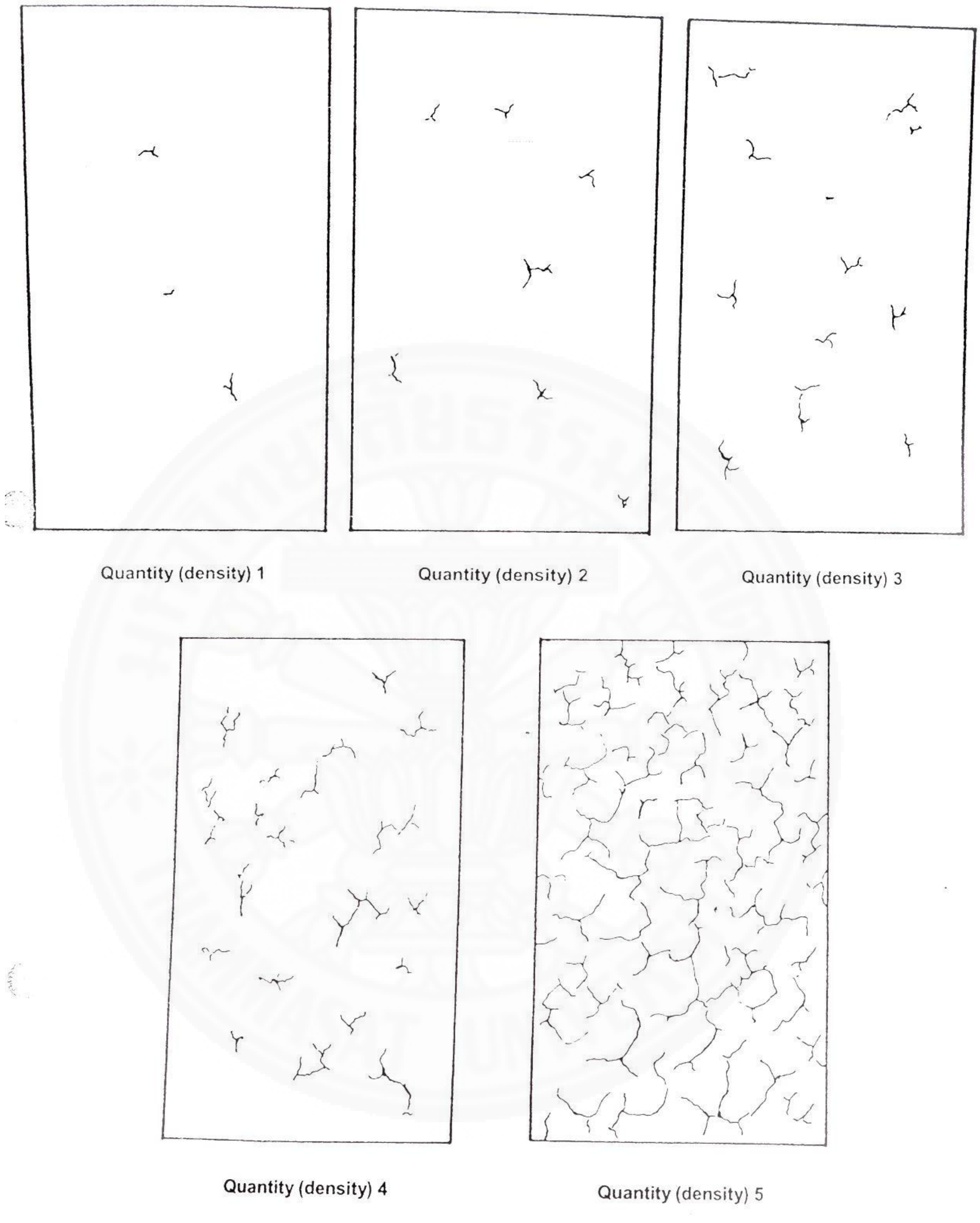


Figure 1 — Cracking without preferential direction
(panels of area 1 dm^2 to 2 dm^2)

Fig. B-10 Cracking without preferential direction

(Reference: ISO 4628-4:2003, Page 4, Figure 1)

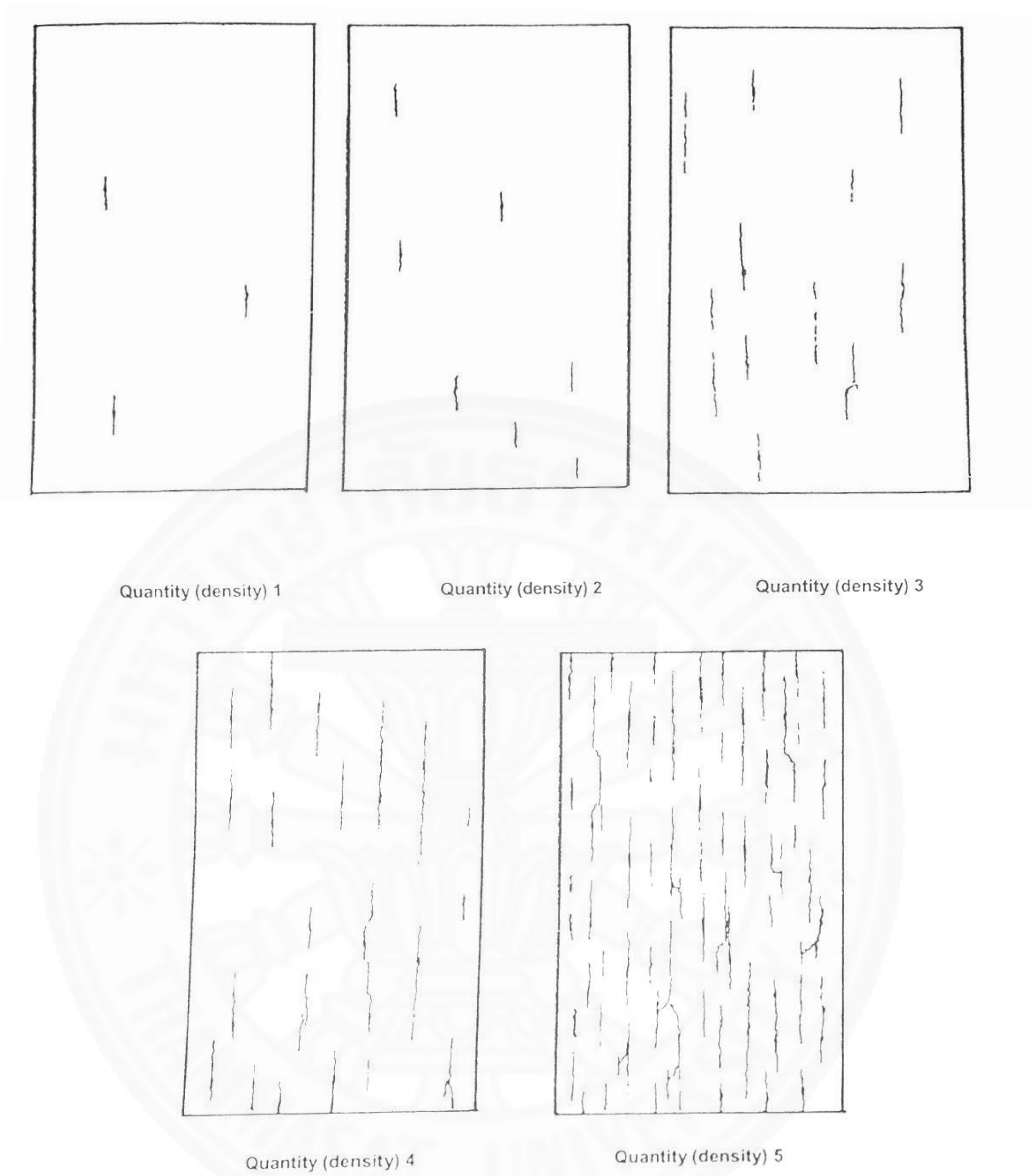


Figure 2 — Cracking in one preferential direction
(for example due to brush marks or wood grain)
(panels of area 1 dm^2 to 2 dm^2)

Fig. B-11 Cracking with preferential direction

(Reference: ISO 4628-4:2003, Page 5, Figure 2)

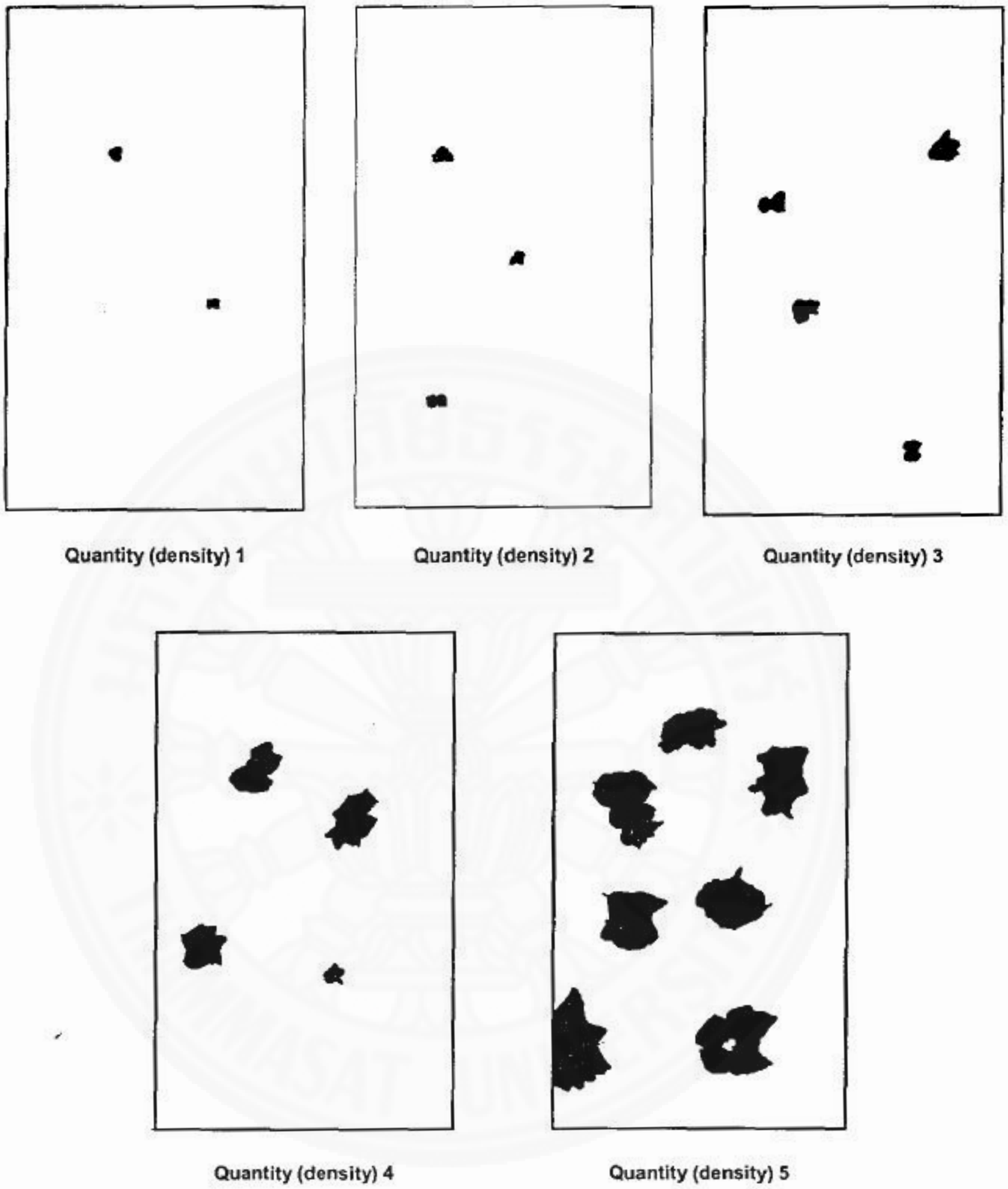


Figure 1 — Flaking without preferential direction
(panels of area 1 dm^2 to 2 dm^2)

Fig. B-12 Flaking without preferential direction

(Reference: ISO 4628-5:2003, Page 4. Figure 1)

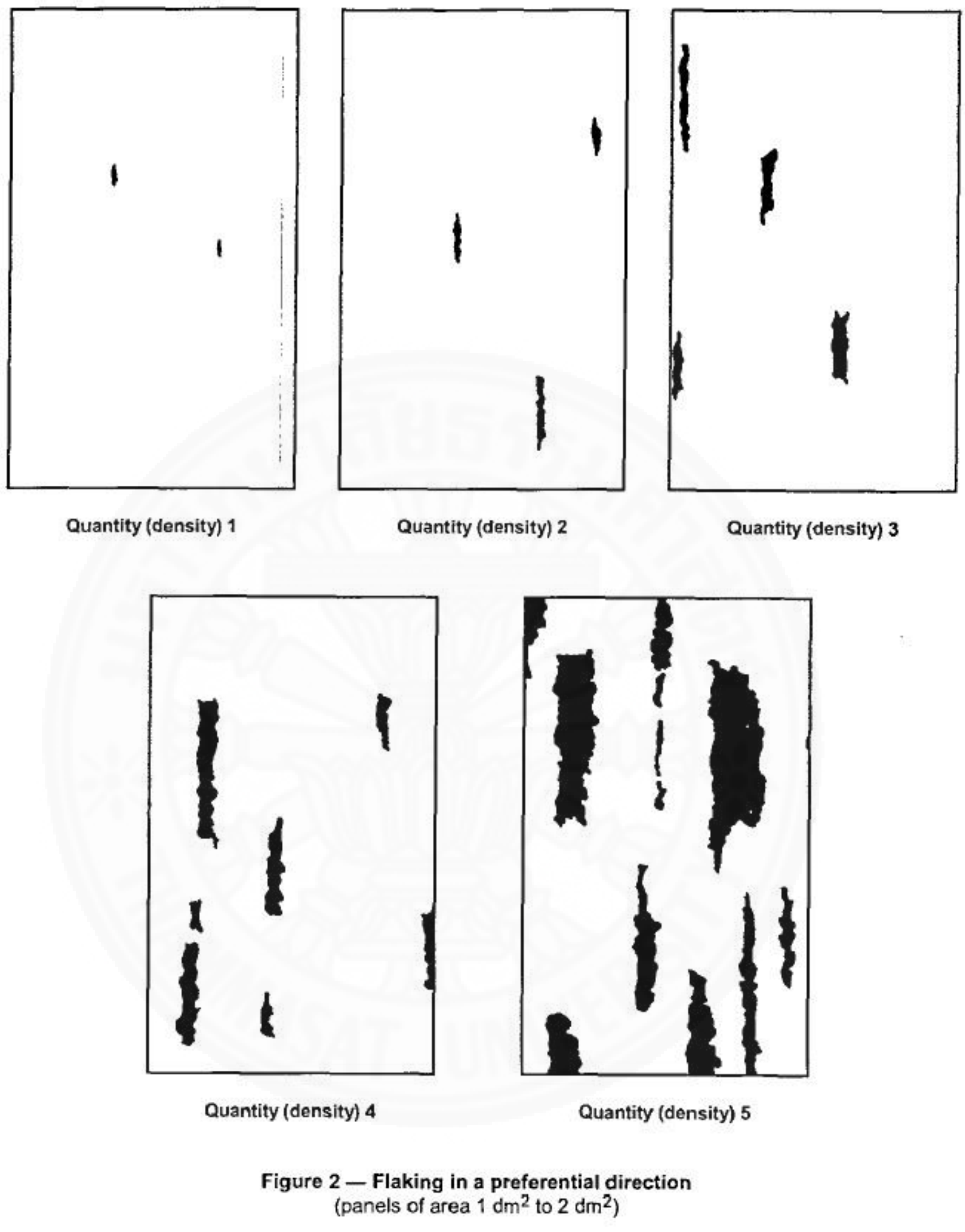


Fig. B-13 Flaking with preferential direction

(Reference: ISO 4628-5:2003, Page 5. Figure 2)