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Vulnerability Assessment of Steel Structures in District 12 of Mashhad City and Prioritizing the Welding Defects Using the Analytic Hierarchy Process

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ABSTRACT

Recently, steel structures have been accounted for a large percentage of the buildings due to their advantages such as higher execution speed and easier construction. In steel structures, welded joints are commonly used and their quality plays a key role in stability of buildings under applied loads. Hence, to increase resiliency of welded steel structures against natural hazards, welded joints quality should be improved. In this article, a statistical study was done on welding defects of different connections in 50 welded steel buildings that were being constructed in district 12 (Mashhad, Iran). The reasons for selecting this district were high rates of construction and high potential of hazards. Actually, initial information about joints importance and weld defects were collected by distributed questionnaires among building designer engineers and weld inspectors. In this paper, we used the Expert Choice software that works according to Analytic Hierarchy Process (AHP) to prioritize weld defects in different connections of the buildings and define management solutions to improve them. The priority results revealed that in the non-rigid connections crater, slag inclusion and spatter are more critical whereas in the rigid connections Lack of Penetration (LoP) and Lack of Fusion (LoF) are more critical than the other welding defects in steel building structures.

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1. INTRODUCTION

In Iran, due to higher execution speed and easier construction, steel structures account for a large percentage of the buildings. Unfortunately, since the builders in the private sector claim that building is aprofitable industry, they endeavor to minimize building costs while increasing the construction speed under any circumstances. This would then result in discarding industrial welding while employing less experienced welders with low salary in the building construction. The final results of such actions in the welded connections of the buildings will be the loss of welding quality and vulnerability of the buildings against seismic loads [1, 2]. Except financial problems in the private sector for the building staff, there are other reasons that contribute to reduction of the welding quality in the construction industry such as improper relationships between the welders and most of the civil engineers, irresponsibility of the welders in the face of upcoming events. To be succinct, all these factors have yielded defective welded connections and the steel buildings safety is faced with serious threats.

This paper is aimed to investigate the field welding quality of the steel buildings in district 12 of Mashhad, Iran to ultimately offer new solutions for improving the current situation. Welding quality in steel connections of the buildings depends on welding defects that are common such as undercut, spatter, crater, LOF, slag inclusion, porosity, over lab, crack, LoP, Arc strick, etc. [2].

Liao [3] Classified welding flaw types with fuzzy expert systems while Kiral and Erim [4] predicted the fracture behavior of the steel beam-to-column

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connections with weld defect using structural integrity assessment procedure (SINTAP) for the analysis of fracture toughnes. Moreover, Cerit et al. [5] studied the stress concentration effects of undercut defect and reinforcement metal in butt welded joint; while there is a plethora of researchers who have examined weld defects in the welded joints behavior at different conditions [6-10]. While the previous literature has merely concentrated on the welding science, the current study is a statistical research elaborating on the welding defects, having a focus on understanding the current situation by prioritizing the welding defects. Figure1 shows common welding defects and their reasons.

2. THE STUDY AREA

Mashhad is the capital of Razavi Khorasan province which is considered as one of the largest and most important Iranian cities, in the north-eastern part of Iran, where dozens of immigrants are annually attracted from smaller towns and villages [11]. New arrivals to the city for financial reasons prefer to buy low-cost housing in resort areas. Price of the land in district 12 of Mashhad is more appropriate which has also attracted developers and construction managers. In the recent years in this district, many buildings have been built and construction is still ongoing. Mainly due to the performance reasons, steel and welded structures in this district are more common. Figures 2 and 3 clearly show study area location.

In recent years, this district has experienced a drop down in groundwater levels and the continuing drought will worsen this phenomenon. Dropping down of groundwater levels will lead to ground settlement which threatens the buildings sustainability [12, 13].

Briefly, Mashhad's District 12 has been selected as a case study because of the massive construction in district 12 of Mashhad because of affordable land and the constructors of most buildings consider steel while the dropping down groundwater levels in the study area that will lead to land subsidence.

This district is one of the populated places because of appropriate land price and having a critical condition; as a result, reviewing and modifying the quality of construction seems indispensable. The welded connections in steel structures play an essential role in maintaining the overall stability of the buildings; hence, we studied the defects and problems associated with connecting welded steel structures in district 12 of Mashhad.

In the study area, examination of the welded connections is executed for a large number of steel buildings which are all consuming a lot of time. Subsequently, 50 running buildings of various construction companies were selected as sample of the study while the investigation of Sama Welding Company helped to determine the percentage of welding defects in different connections for each of the selected buildings.

Welding defect	Reasons	Regulations provisions*	picture
Under cut	- Excessive welding currents - long arc length - High amperage - too high Travel speed - too high Welding voltage - Wrong electrode angle	Iran regulation welding Publication 228 Season 8 part 8-15-1-5	
Spatter	- High amperage - Metal surface contamination - Wet electrodes - Welding being exposed to wind - Long arc length - Magnetic arc blow - Bad Shielding Gas - excessive wind in the welding area	Iran regulation welding Publication 228 Part 3-11-2	
LOF (Lack Of Fusion)	- high electrode diameter - too low welding voltage and/or current too low travel speed - excessive oxide on plate - Inappropriate amperage - Unsuitable angle to electrode during welding	Iran regulation welding Publication 228 Part 8-15-1-2	
Crater	- Abruptly stopping arc welding - Too fast a cooling rate - Lack of welder skill - Inoperative crater filler (GTAW)	Iran regulation welding Publication 228 Part 8-15-1-1 & 8-15-1-3	
Slag inclusion	- No cleaning slag from a previous welding pass - Inappropriate ampere - Incorrect chosen electrode	Iran regulation welding Publication 228 Season 3 Part 3-7	
Porosity	- Excessive welding currents - Welding over slag from covered electrode - Failure to remove glass between weld passes - Welding by long arc - Electrode coating fractures - Oil, heavy rust, scale, etc. on plate	Iran regulation welding Publication 228 Part 8-15-1-6	
Over lab	-Unsuitable and low-speed welding -Unsuitable angle to electrode during welding - high electrode diameter - low amperage	Iran regulation welding Publication 228 Season 3 Part 3-7	
Cracking	- Tensile stresses caused by the contraction - Existing impurity such as sulfur, phosphorus and zinc in metal or electrode - Unsuitable width to depth ratio - Incorrect wire chemistry - too small Weld bead	Iran regulation welding Publication 228 Part 8-15-1-1	
LoP (Lack of Penetration)	- too low or too much welding current too narrow Weld joint - Inappropriate ampere - Small roots - high electrode diameter	Iran regulation welding Publication 228 Season 3 Part 3-7	
Arc strick	-Accidental or intentional collision electrode to base metal	Iran regulation welding Publication 228 Season 3 Part 3-10	

*** Iran regulation of welding construction**

Figure 1. Common welding defects which seen in buildings and their happening reasons

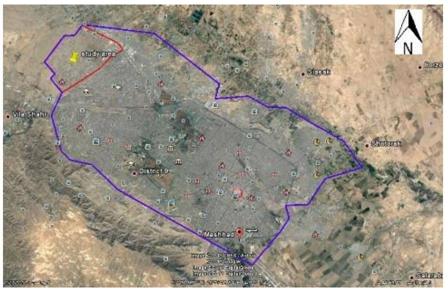


Figure 2. The study area located in north west of Mashhad, Iran

Figure 3. Geographic location of Mashhad city in the north-eastern part of Iran

3. MATERIALS AND METHODS

To prioritize the defects in different connections of the buildings, importance of connections and the percentage of defects in each of them will be determine. The primary data was collected by two different questionnaires. The first questionnaire was to determine the percentage of each defect in the connections that required tests carried out by the welding inspector. To answer this questionnaire, the weld inspectors used different tools and methods such as visual inspection, penetrant testing, ultrasonic testing and electromagnetic testing to reconnoiter the defects and compare them with the standard range (Figure 4) [14]. It was noted that the study area has about 70 steel buildings where welding test is possible; therefore, according to the Cochran formula, 50 steel buildings were randomly tested [15].

The second questionnaire was answered by experienced structural designer engineers. In this questionnaire, the respondents assigned a number between 1-9 to welding defects in different connections. Accordingly, the least important option scored one whereas the most important option scored 9 while the importance between them scored 1 to 9. It is of note that the Mashhad has about 1200 structural designer engineers; therefore, according to the Cochran formula, about 600 of them were randomly selected to answer this questionnaire [15]. The percentages indicated by the weld inspectors multiply the importance of defects in the connections and numbers in Table1 have been prepared to compare different defects in different connections using Expert Choice software [16].

Furthermore, a third questionnaire was distributed among some experienced structural designer engineers. If a joint has a key role in sustainability of the building, it takes number 100 and the least important scored 10 and the importance between them scored 10-100. Figure 5 demonstrates the final scored for different connections.

Figure 4. Welding defects tested by different methods (left to right: MT, UT and Penetration test)

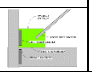
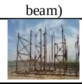
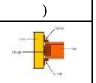
name	connection	score	name	connection	score	name	connection	score
a	Built up column (triple I) 	87	b	Cover plated column 	92	c	Battened column with flat bars 	93
d	Columns stiffened Seat 	85	e	Butt weld in cover plate (column) 	85	f	Double web angle simple connection 	75
g	Columns flange plate splice 	87	h	Shear stud 	58	i	Continuous welding in HC places 	67
j	Columns stiffened bases 	77	k	Bracing connection s to a gusset plate 	88	l	Bracing connections (gusset plate weld connections to column and beam) 	88
m	Slot weld in Cover plated column 	40	n	top angle connection (flexible connection) 	37	o	Top flange plate (moment connection) 	93
p	Bottom flange plate (moment connection) 	93	q	Built-up box column 	88			

Figure 5. Importance of steel connections related to building sustainability

TABLE 1. The final numbers for welding defects in different connections

connections	crater	Under cut	L O F	spatter	Slag inclusion	porosity	Over lab	LoP	Arc strick	Insufficient welding leg	Inadequate During Welding
Built up column (triple I)*	300	75	60	120	35	25	35	560	60	1	160
Cover plated column** (fillet weld)	200	75	35	180	35	49	56	1	40	80	200
Battened column with flat bars***	300	100	30	180	50	50	50	1	60	21	1
Columns bases (Fillet weld) which attach the column to the base plate	140	175	105	360	120	28	120	63	49	360	9
Columns flange plate splice	35	14	35	240	560	35	28	640	45	1	1
Double web angle simple connection, Fillet weld in the vertical position	140	130	147	280	304	56	280	1	56	78	378
Columns splice connection (Fillet weld)	70	84	56	280	140	42	280	1	40	54	18
Shear stud (Fillet weld)	425	95	48	120	60	102	15	1	24	270	24
Continuous welding in HC places (Fillet weld)	75	72	42	180	49	42	35	1	42	210	378
Columns stiffened bases, Fillet weld which attach column to base plate	104	112	136	450	160	40	120	1	150	189	18
Bracing connections to a gusset plate (Fillet weld)	40	72	40	300	64	24	80	1	160	225	27
Bracing connections, Fillet weld in gusset plate weld connections to column and beam	40	56	40	300	80	32	80	1	160	236	45
Slot weld in the Cover plated column	150	15	120	210	450	175	100	480	10	45	45
top angle connection (fillet weld), flexible connection	128	108	50	250	65	85	70	1	35	84	228
Top flange plate, complete penetration groove weld (moment connection)	27	36	90	45	135	108	1	171	9	1	9
Bottom flange plate, complete penetration groove weld (moment connection)	18	18	72	18	45	63	1	90	1	1	1
Built-up box column (Fillet weld)	49	21	49	6	1	28	1	56	1	9	1

* part (a) in Table 3 is composed of three IPE Sections connected to each other by Single sided partial penetration butt weld.

**part (b) is similar to part (a) in Table 3, but with another IPE section between the two other IPEs. These three sections are welded together by groove welds, and column cover plates connect the two exterior sections by fillet weld.

*** part (c) in Table 3 is composed of two IPE Sections connected to each other by the distance with flat bars by fillet weld.

The end of collecting initial data by questionnaires validity, reliability and compatibility of data was tested. Reliability confirmed by 0.81 Cronbach's alpha coefficient in SPSS software. Also, validity and compatibility of questions was confirmed by the opinion of the professors and experts.

4. THE ANALYSIS METHOD

To evaluate the collected data, the Analytic Hierarchy Process (AHP) was adopted which is a flexible, robust, and simple method used in decision making when faced with several options competitor.This technique examined the complex issues based on their interactions and solved them by a simple way.

The AHP method is based on three steps: first, the structure of the model; second, the comparative evaluation of the alternatives and the criteria; third, synthesis of the priorities. Therefore, in this paper, the expert choice software was used that works according to the Analytic Hierarchy Process (AHP) [16-18].

In the first step, a sophisticated decision problem is structured as a hierarchy. This method breaks down a sophisticated decision construction problem into the hierarchy of objectives, criteria, and alternatives. These decision elements make a hierarchy of the structure, including the goal of the problem at the top, criteria in the middle and the alternatives at the bottom of this hierarchy.

In the second step, the comparisons of the alternatives and criteria are made. Let $C=\{C_j|j=1,2,...,n\}$ be the set of criteria. The result of the pairwise comparison on n criteria can be summarized in an (n×n) evaluation matrix A in which every element $a_{ij}(i,j=1,2,...,n)$ is the quotient of weights of the criteria, as shown in Equation (1).

$$A=\begin{bmatrix} a_{11} & \cdot & a_{1n} \\ \cdot & \cdot & \cdot \\ a_{n1} & \cdot & a_{nn} \end{bmatrix}, a_{ii}=1, a_{ji}=\frac{1}{a_{ij}}, a_{ij}\neq 0 \quad (1)$$

At the third step, the mathematical process commences to normalize and find the relative weights for each matrix. The relative weights are given by the right eigenvector (ω) corresponding to the largest eigenvalue (λ_{max}), as follows [19]:

$$A\omega=\lambda_{max}\omega \quad (2)$$

5. PRIORITIZATION OF THE WELDING DEFECTS

Priority of defects in non-rigid and rigid connections of steel buildings according to Table1 presented in Table 2.

As mentioned earlier, the purpose of this analysis is to prioritize the welding defects in the steel connections of the buildings using the Expert Choice software. The built model in the software had two layers; the first layer includes different connections that were compared pairwise according to the scores presented in Figure 6. In the second layer, different welding defects were compared in different connections according to the scores provided in Table 1 (Figure 7).

In fact, a three-time analysis was undertaken. During the first time, all the rigid and the non-rigid connections were considered. During the second time, only the non-rigid connections were taken into account and the third time we just focused on the rigid connections.

In the first layer analyses, we used Figure 6 data and compared different rigid and non-rigid connections. Figure 6 displays o, p, and q connections that are rigid and bear more importance in comparison with the non-rigid joints; therefore, they need to have more quality.

C, b, k and l connections have the highest importance in the non-rigid connections, which means they need more attention and control to have an acceptable quality. Figure 8, shows the results of the rigid and non-rigid connections being analyzed together. Table1 data was inserted to analyze the model and was compared pairwise in the second layer.

Spatter defect has less structural importance but as it can be seen it has more critical condition than the other defects. In Table 1, a big number was assigned to spatter, which is why we should control that and decrease the percentage of this defect. Crater, LoP, and slag inclusions, respectively have 12.4, 11.6 and 10.8% and seem critical. In addition, crater, LoP and slag inclusions have significant structural importance so these defects should be controlled as soon as possible by new methods and recommendations.

By elimination the rigid connections from the analyses, the results have changed significantly and as it can be observed in Figure 9:

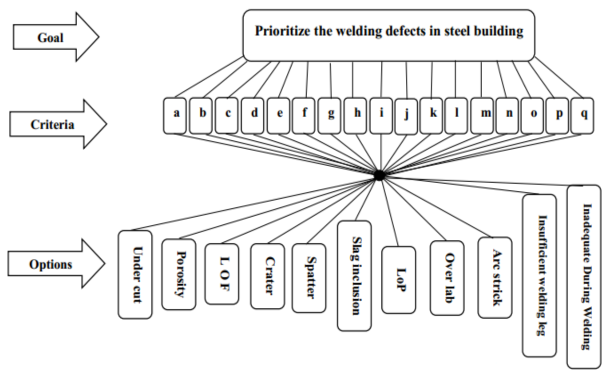


Figure 6. Hierarchical structure for welding defects prioritization related to steel buildings

TABLE 2. Defects priority in connections according to Table 1

non-rigid connections				rigid connections			
Defects priority	**ave**	**min**	**max**	**Defects priority**	**ave**	**min**	**max**
LoP	435	N	640	LoP	105.5	56	171
Spatter	246	120	450	Under cut	70	49	90
Slag inclusion	155	35	560	porosity	66	28	108
Crater	153	35	425	Slag inclusion	60	1	135
Insufficient Welding leg	154	N	360	spatter	31	18	49
InadequateDuring Welding	127.5	N	378	Crater	25	18	36
Over lab	96	15	280	L o F	23	6	45
Under cut	84.5	14	175	Insufficient welding leg	9	N	9
LoF	67.5	30	147	InadequateDuring Welding	4.5	N	9
Arc strick	66.5	10	160	Arc strick	3	1	9
porosity	56	24	175	Over lab	1	1	1

N= Non-defined defect for some connections

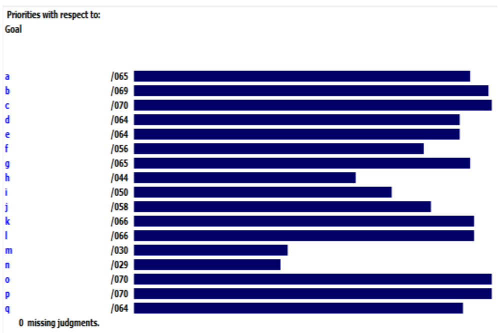


Figure 7. Connections priorities according to the scores presented in Table1

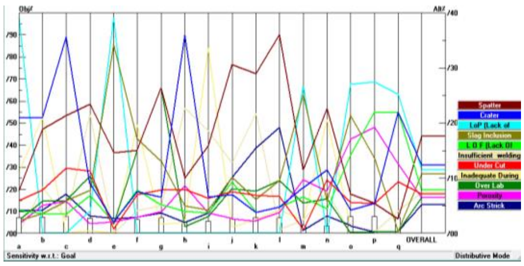
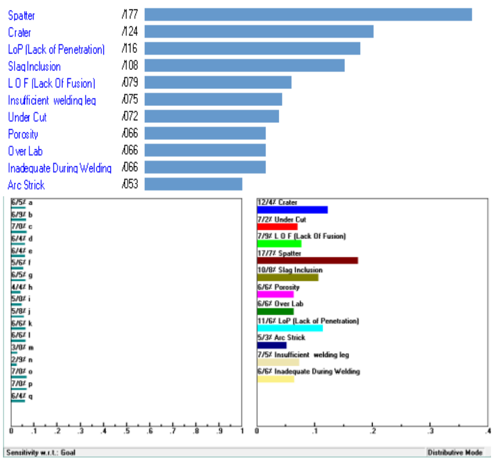


Figure 8. Prioritize welding defects related to rigid and non-rigid connections analyses



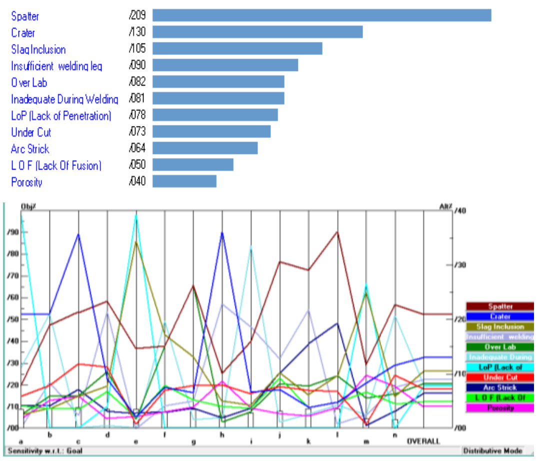


Figure 9. Prioritize welding defects related to non-rigid connections analyses

- The percentage of the spatter increased from 17.7 to 20.9% meaning that the industrial welding (rigid connections) slightly controls the spatter defect.
- The percentage of LoP decreased from 11.6 to 7.8% that means welding in the site project has less LoP defect. As Table 1 shows, in the building, LoP was not defined as a defect most of the time.
- The percentage of over lab increased from 6.6 to 8.2% implying that welding in the site project should cast more control over the lab defect to make it less critical. By industrial welding, this defect could be normalized.

When the rigid connections were analyzed separately, LoP, LoF and porosity respectively had 26.6, 19.4 and 16.4% that were more critical than the other defects in this kind of connections as industrial welded connections. Figure 10 shows the results associated with the rigid connections analyses.

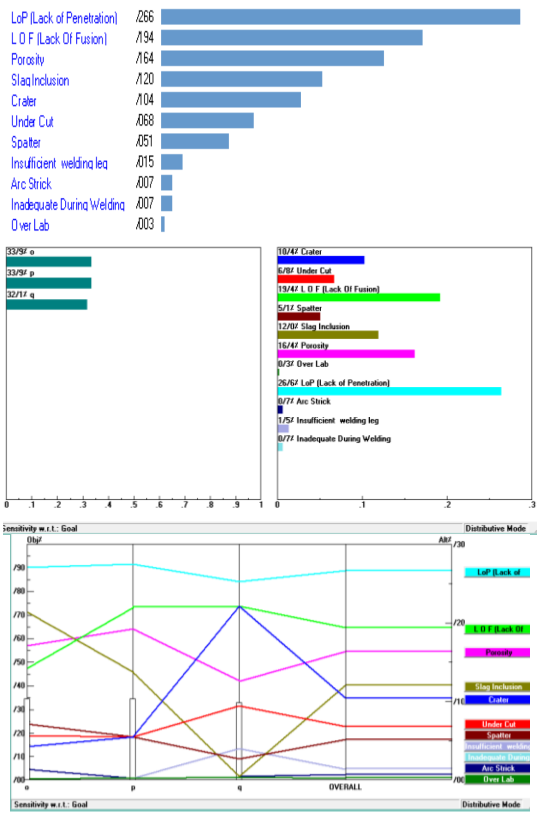


Figure 10. Prioritize welding defects related to rigid connections analyses

6. CONCLUSIONS

The analyses show that the results of the rigid connections that have been implemented industrially are more different from that of the non-rigid connections being implemented in the site projects.

1. In the non-rigid connections have been implemented in the site project, the highest percentage of the spatter defect as observed while in the rigid connections it has an acceptable percentage. Although this defect does not exert a significant structural impact on the stability connection, it could be a sign for the other defects.
2. The crater defect in the non-rigid connections is critical by 13% requiring a new solution to have it decreased in the welding steel joints. If the crater defect combined with the star crack, it will be more critical and welding regulations never accept that. By modifying the method of welding in the site project, using end beam studs, and industrial welding, it would possible to lower the crater defect percentage by about 50% and then it will be out of the critical condition.
3. Although the LoP defect in the rigid welding connections has the highest percentage, by referring to Table 2, it is understandable that in the non-rigid welding connections not been defined. According to Table 1, the LoP defect in the non-rigid welding connections scored one, which means this defect in that kind of connections not been defined. Therefore, it is not possible to conclude that by the industrial welding connection, the LoP defect becomes more critical.
4. The LoF defect in the industrial rigid welding connections seems more critical than the non-rigid welding connections being implemented in the site project, but by looking at Table 1, it gets clear that in all the cases the LoF defect has received the same score. Because of high percentage of the spatter defect in the non-rigid welding connections, the LoF defect seems less critical in this kind of connections. Consequently, assuming that the site project welding is better than the industrial welding concerning the LoF defect is very wrong.

Having analyzed the data, the results are summarized as follows:

- The industrial welding should be used as much as possible instead of welding in the site project.
- It is necessary to oblige all the welding steel buildings to obtain the weld certificate from the welding inspection companies.
- We should adopt more modern and up-to-date welding methods.
- It is imperative to calibrate the welding machine before welding.
- There should be some modifications in the contract between the employer and the welders.
- We should be stricter in awarding and recognition of the welders' welding qualification.

- It is necessitous to repair the defects in accordance with the welding regulations.
- Weld education should be added to civil engineering (terms time) courses in the universities.

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Analytic Hierarchy Process

چکیده

اخیرا، سازه‌های فولادی به دلیل مزایای ویژه مانند سرعت بالا و راحتی ساخت درصد بالایی از ساختمان‌ها را در بر گرفته‌اند. در سازه‌های فولادی، اتصالات جوشی عمدتا مورد استفاده قرار می‌گیرند که کیفیت جوش‌ها نقش اساسی در پایداری ایفا می‌کنند. بنابرین برای افزایش مقاومت این‌گونه سازه‌ها در برابر حوادث طبیعی باید کیفیت اتصالات جوشی را بهبود بخشید. در این پژوهش، مطالعه‌ای آماری بر روی عیوب جوش در اتصالات مختلف مربوط به 50 ساختمان فولادی جوشکاری شده در منطقه 12 شهرداری مشهد، ایران، انجام شده است. دلایل انتخاب این منطقه، بعنوان مورد مطالعاتی، نرخ بالای ساخت و ساز و پتانسیل بالای خطرات طبیعی در آنبوده است. همچنین، اطلاعات اولیه مربوط به اهمیت انواع اتصالات و عیوب جوش با توزیع پرسشنامه بین مهندسان عمران طراح و بازرسان جوش جمع‌آوری شده است. در این مقاله، نرم‌افزار Expert Choice انتخاب شده که براساس تحلیل سلسله مراتبی(AHP) به اولویت‌بندی انواع عیوب جوش در اتصالات مختلف ساختمان می‌پردازد تا راهکارهای مدیریتی مناسب جهت بهبود وضعیت آن‌ها ارائه گردد. نتایج نهایی نشان می‌دهند در اتصالات غیرصلب، عیوب بریدگی کناره و حبس سرباره و پاشش بحرانی‌تر بوده‌اند در صورتی که در اتصالات صلب عدم نفوذ و امتزاج ناقص بحرانی‌تر به نظر می‌آیند.

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