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Health Monitoring of Welded Steel Pipes by Vibration Analysis

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ABSTRACT

In the present work, structure health monitoring (SHM) of welded steel pipes was used to diagnose their state via vibration based damage detection techniques. The dynamic quantities such as Frequency Response Functions (FRFs), mode shapes and modal parameters from structural vibration to detect damage were measured, set on linear averaging mode, with a maximum frequency of analysis of 3.2 kHz. Two most commonly used welding techniques were used, namely: shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). Static tests were performed to assure the quality of welded steel pipes. These tests include three point bending test (3PB), face bending, and tensile testing. In addition, X- ray images were utilized as a non-destructive testing (NDT). The results showed for non-cracked pipes, having the first three modes, the higher damping frequency and the lower damping ratio. This reflects the difficulty of dissipating energy at higher frequencies. Also, it was found that SMAW gives higher damping ratio (7.418%) as compared to GTAW joints (7.220). So, the latter joints have higher stiffness than former ones. The results demonstrated that the FRFs technique is a potentially powerful tool for damage detection and health monitoring of welded steel structural pipes.

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1. INTRODUCTION

In the last few decades the possibility of continuous assessment of the integrity of complex structures has fostered intense research in the field of Structural Health Monitoring (SHM) and several SHM approaches based on different inspection techniques have been proposed [1]. The basic concept of SHM consists of inspecting a structure using permanently attached or embedded sensors. It is evident that a reliable SHM system can potentially alter the way complex structures are operated and maintained, because an optimal functionality can be guaranteed, minimizing the time in which the structure is out of service and reducing significantly plant outage, as well as the costs associated with conventional inspection. SHM can also be useful in estimating the remaining life of components and can be used to assess whether their replacement is needed or not. Hence, SHM appears extremely attractive for a wide number of engineering applications ranging from the aerospace industry (e.g. health monitoring of the fuselage of aircraft while in service) to the chemical and power generation industries (e.g. inspection of storage tanks, pressure vessels and pipelines). The feasibility of an SHM methodology is strongly dependent on the possibility of effectively inspecting the structure from only a few locations. Furthermore, it is crucial that the data recorded can be reliably interpreted to make damage detection possible. In addition, the development of a reliable SHM technology poses new challenges in several different fields, such as development of smart materials, integration of sensors with the structure to be inspected, and acquisition and transmission of large amounts of data [1, 2].

Ultrasonic guided waves offer the possibility of inspecting large areas from a small number of sensor positions and guided wave inspection is now an established approach in NDE. In addition, it has been demonstrated that acoustic emission signals in typical aircraft structures are a combination of the fundamental A_0 and S_0 modes and that long propagation distances can be achieved [3, 4]. Guided wave inspection is therefore attractive for the development of an SHM

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system for the inspection of complex structures. However, guided wave inspection of complex structures is difficult as the reflections from different features overlap. Hence, the ultrasonic time traces become very complicated and damage detection is a difficult task (e.g. the reflection from the damage site can be masked by reflections coming from benign features). Cawley et al. [5] uses Lamb waves to detect corrosion in pipelines. Not only does Cawley specify the type of damage, but he also quantifies the extent of detectable damage. In particular, the extent of damage is quantified as a value relative to the dimension of the pipe diameter and the pipe wall thickness, producing a dimensionless measure of damage extent. This definition of the damage to be detected directly influences many parameters in the test procedure. Katafygiotis and Lam [6] have built and tested a two-story structure made of aluminum bars and plates. They introduce damage by removing column bars in such a way as to avoid torsional motion. The bar removal corresponds to a 25% stiffness reduction. Two stiffness parameters and two damping ratios are used as model parameters. Finite element simulations are used to calculate the model parameters, which are then used to update the analytical model of the structure. Burton et al [7] present two methods of determining the stiffness change of a damaged structure using lower vibration modes. The authors assume a priori knowledge of the undamaged structure's stiffness matrix, mass matrix, frequencies and mode shapes. Furthermore, the damage locations are also assumed as known. Karthik et al [8] focused on tensile property, toughness; microhardness and microstructure of the each welding process of weld joints are studied and compared with those properties of each process related to the base metal, which shows the better welding process on stainless steel. The effect of varied welding parameters was examined and discussed in order to be able to predict the service behavior (performance) of welded low carbon steel samples. The results have shown that the selected welding parameters have significant effect on the mechanical properties of the welded samples [9].

In the present work, health monitoring of welded steel pipes by vibration analysis based damage detection techniques was studied. These techniques are based on the principle that damage alters the dynamic properties of the structure such as mass, stiffness and damping. It is therefore feasible to utilize the measured dynamic quantities such as FRFs and modal parameters from structural vibration to detect damage. Steel pipes made from carbon steel (ASTM A 106 grade B) were used in the present work. This type of steel is highly recommended for high pressure as well as high temperature applications such as pipelines in boilers and oil industry. Two most commonly used welding techniques were used, namely: SMAW and GTAW. An artificial crack 2 mm in depth, and 1mm wide was made in the welded region. Static tests were performed to assure the quality of welded joints. These tests include: 3PB, face bending, tensile testing, and buckling tests. All the tests were made in accordance with the ASTM specifications. Dynamic tests were performed via an impact on a pipe, where three uniaxial accelerometers were kept at a certain locations as a reference. The data were acquired through FFT pulse analyzer, set on linear averaging mode, with a maximum analysis frequency of of 3.2 kHz.

2. EXPERMENTAL PROCEDURE

2. 1. Materials and Processing Steel pipes made from carbon steel (A 106 grade B) were used in the present study. Its composition and mechanical properties are shown in Tabled 1 and 2, respectively. Carbon steels as a group are perhaps more heterogeneous than constructional steels, and their properties are in many cases relatively unfamiliar to the designer. In some ways, carbon steels are an unexplored world, but to take advantage of these materials will require an increased attention. The materials employed are location dependent in the same structure for effective and economical utilization of the special properties of each material. This type of steel is highly recommended for high pressure as well as high temperature applications such as pipelines in boilers and oil industries.

Two of the most commonly used welding techniques were used, namely SMAW and GTAW to weld the steel pipes. SMAW is a process that melts and joins metals by heating them with an arc established between a sticklike covered electrode and the metals.

This is often called stick welding. The electrode coating deoxidizes and provides a shielding gas in the weld area to protect it from oxygen and nitrogen in the environment. Electrodes are available for welding most plain carbon, low alloy and stainless steels, some nonferrous metals, and a wide range of maintenance and repair applications. GTAW is a process that melts and joins metals by heating them with an arc established between a no consumable tungsten electrode and the metals. The torch holding the tungsten electrode is connected to a shielding gas cylinder as well as one terminal of the power source.

GTAW is used for a wide variety of metals and applications, particularly aluminum, copper, brass, magnesium, titanium and high alloy metals. It is especially suited for thin metals as well giving highest quality welds. More details about processing of these techniques are given elsewhere in literature [10-13].
A steel pipe after welding by these techniques is shown in Figure.1. An artificial crack with depth of 2 mm was made in the welded region.

2. 2. Materials Characterization Static tests were performed to assure the quality of the two welded joints (SMAW and TIG). These tests include: three bending test (3PB), face bending, tensile testing, and buckling test (universal testing machine (Make: FIE-BLUE STAR, India; Model: UNITEK-94100). All the tests were made in accordance with the ASTM specification (39 mm diameter and 45 mm long).

In addition to nondestructive tests,, x- ray and liquid penetration inspection methods were performed. Dynamic tests were performed via an impact on a pipe, where three uniaxial accelerometers were kept at a certain location as a reference, and the pipe was impacted at 24 points. The data were acquired through FFT pulse analyzer, set on linear averaging mode, with a maximum frequency of analysis of 3.2 kHz.

TABLE 1. Chemical composition and mechanical properties of A106 steel (wt. %)

Comp.	A106
C	0.30
Si	0.1
Mn	0.29
P	0.3
S	0.05
Cr	0.40
Cu	0.40
Mo	0.1
Ni	0.40
Fe	B

TABLE 2. Mechanical properties of A106 steel

Properties	A106
Yield strength, MPa	240
Tensile strength, MPa	415
Elongation %	30

3. RESULTS AND DISCUSSION

3. 1. Static Testing of Welded Samples

3. 1. 1. Buckling Test of Welding Specimens at 85A The SMAW and GTAW welding specimens before and after preceding the bulking test are shown in Figure 2. The applied tensile load and extension are recorded during the buckling test for the calculation of stress and strain, shown in Figure 3.

3. 1. 2. Three Point Bending Test of Welding Specimens at 85 A The three point bending test is the more important testing to show the properties of the welding specimens such as bending strength and young modulus. The experimental setup of the three points bending fixture of the SMAW and GTAW welding specimens before and after preceding the bending is shown in Figure 4. The applied tensile load and extension are recorded during the bending test for calculation of stress and strain, shown in Figures 5 and 6. However, steel can be welded in different welding processes which results in having different strength. So the effect of welding on GTAW and SMAW welding process on steel changes its properties.

a b

Figure1. Pipe after welding by a) SMAW and b) GTAW techniques

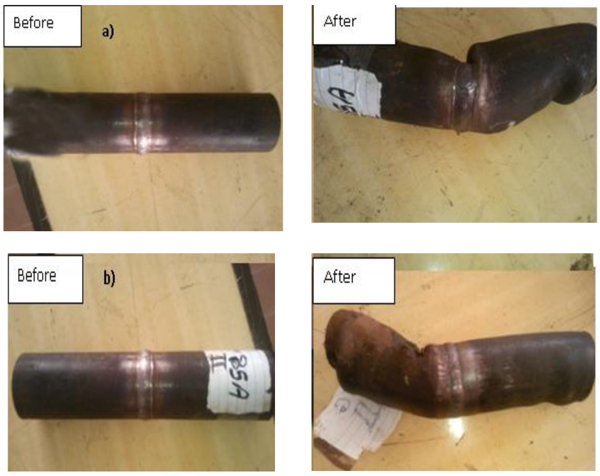
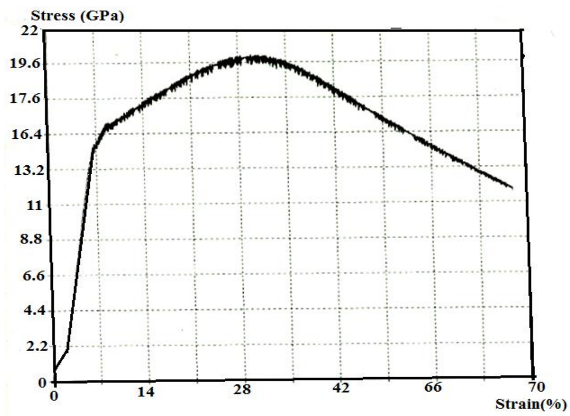
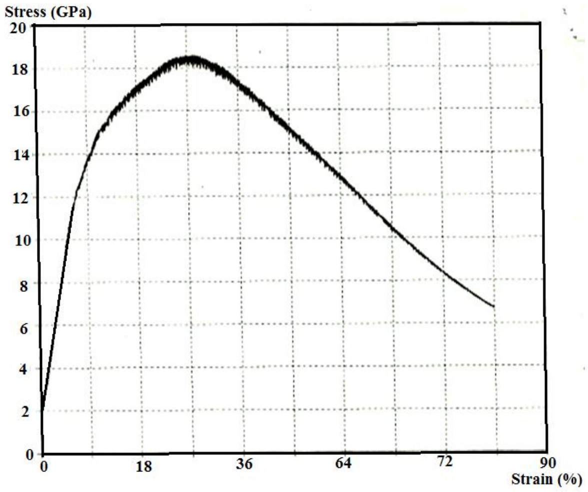


Figure 2. Steel pipes a) SMAW b) GATW welding techniques



(a)



(b)

Figure 3. load extension curve of steel pipes after buckling a) SMAW and b) GTAW welding techniques

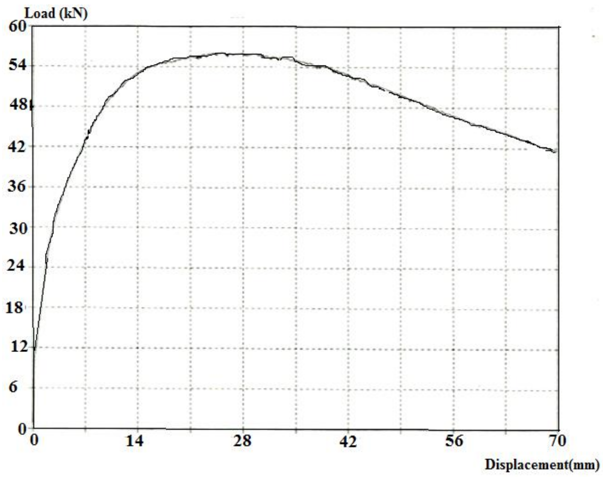
(a) (b)

Figure 4. Steel pipes a) before and b) after 3 point bending test of GTAW welding

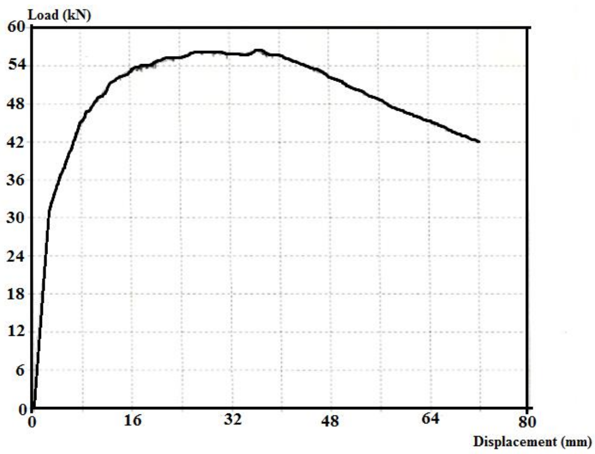
3. 1. 3. Tension Test for Welding Techniques at 85A Tensile tests are carried out by applying longitudinal or axial load at a specific extension rate to a standard tensile specimen with known dimensions (gauge length and cross sectional area perpendicular to the load direction) till failure.

The applied tensile load and extension are recorded during the test for calculation of stress and strain, shown in Figure 7. The specimen is grooved at some small distance for holding the machine's specimen holder. To hold and give the tensile load on it, it will elongate and fracture some after load it is imposed.

When the specimen reaches its ultimate tensile load, slightly losses its strength as shown on the graph of the tensile machine. After reaching the ultimate load, the curve suddenly propagates on opposite direction. Then it will break at certain load rate on the load scale and it is called the fracture load or strength of the specimen. The mechanical properties of the weldment of SMAW and GTAW pieces were analyzed and showed the strengthened value closer to that of parent metal. The data from tensile testing are given in Table 3. The average value for specimens of each process is tabulated on the same table. Then, the average values represent the SMAW and GTAW welding of tensile property of the stainless steel plate results. It plots the difference between tensile property of two welding and their results that nearer to the actual or base metal tensile properties.It is desired to compare efficiency of welding processes and shows the yield strength and ultimate strength of GTAW welding properties; which were better than the SMAW welding properties. Based on obtained data the GTAW welding steel 106 grade having better tensile strength than SMAW welding.



(a)



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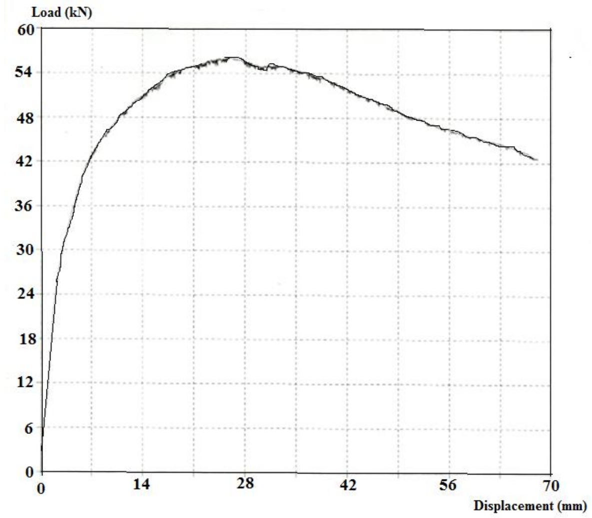


(c)

Figure 5. Load extension curve of steel pipes after bending a) Control b) SMAW at 85A c) SMAW at 105A

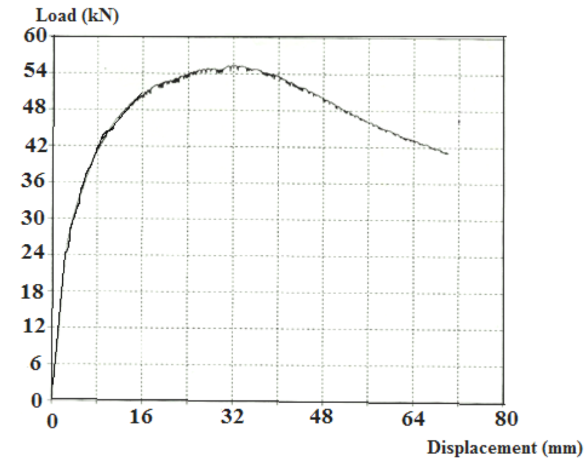
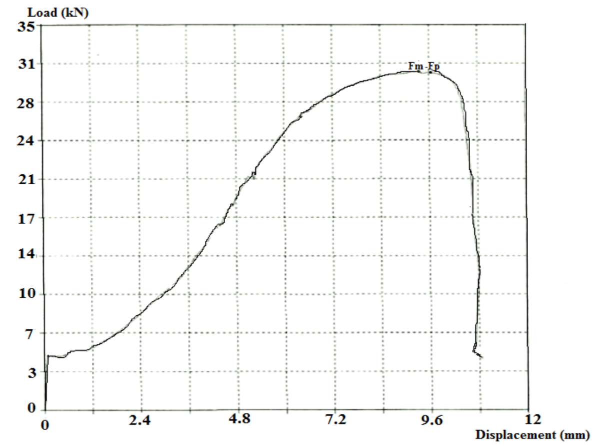
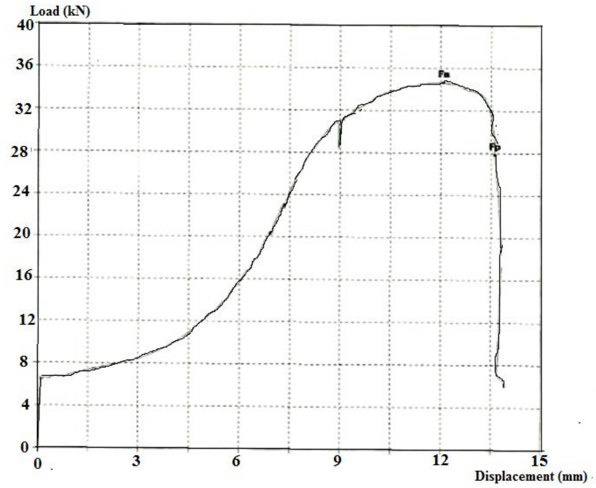


Figure 6. Load extension curve of steel pipes after bending GTAW welding



(a)



(b)

Figure 7. load extension curve of steel pipes after tension a) SMAW and b) GTAW welding

3. 1. 4. X-Ray Radiography of Welded Samples
This test was carried out on the welded samples using SMAW and GTAW techniques at 85 A. The XRD of the welded sample by these techniques is shown in Figure 8.

3. 2. Dynamic Testing of Welded Samples at 85 A
In tested specimens, the first four resonant frequencies of SMAW and GTAW welded joint are measured using inductive hammering technique as shown in Figures 9 and 10, and Tables 4 and 5. Experimental studies in the area of the dynamic analysis of cracked pipes are carried out by the measuring four natural frequencies and the associated damping ratios. The experimental results are obtained for the length ratio in the states of crack location. The crack was initiated for each pipe with fine saw cut in the stated depth ratio. At each step, the depth of crack is checked by direct measurements. It can be observed that the natural frequencies decrease monotonically as the current cross distance of the crack decreases monotonically close to antinodes of the vibrating pipe modes and the stated crack increases as shown in Table 4 and Figure 9.

Figure 10 shows the frequency response function curve (FRF) recorded in a specimen ASTM without and with crack. It can be noted that the lowest frequency and lower damping compared with the uncracked specimen is due to the minimum and maximum values of maximum tensile stresses and stiffness in this type of welding. In view of different type of welding, the rate of change of the frequency is relatively low.

The non-welded steel pipes (ASTM A106) have shown to attain relatively high damping ratio (6.876%) as compared with welded joints (5.958 for GTAW as 6.173 for SMAW, 85A). For cracked pipes of GTAW, crack results in a reduction of damping from 8.110 to 6.569 %. Such an unexpected result may be attributed to the small depth of the crack (2mm) compared to the pipe thickness all most one fourth of pipe thickness. For SMAW, crack has the same effect as in GTAW regardless of welding current. However, cracked pipes welded lay 85 A . It was found that in uncracked pipes, having the first three modes, the higher damping frequency, and the lower damping ratio. This reflects the difficulty of dissipating energy at higher frequencies. SMAW joints give higher damping ratio (7.418%) as compared with GTAW joints (7.223). So, the latter joints have higher stiffness than former ones.

TABLE 3. Testing results of welding processes

Test specimen	Size (mm)	Length (mm)	Yield load (kN)	Peak load (mm)	Ultimate tensile load(kN)	Elongation (%)	Welding effecincy (%)
SMAW	39	45	53	69	33.8	41.2	88.12
GTAW	39	45	52.4	67.39	34.7	46.6	93.30

TABLE 4. The damping and frequency of SMAW technique

Mode	Without crack		With crack	
	Damped Frequency (Hz)	Damping (%)	Damped Frequency (Hz)	Damping (%)
1	13.7857	7.41832	10.52961	8.11522
2	27.47653	5.58863	25.59298	6.13182
3	164.88411	4.52446	152.58520	5.51268
4	235.49603	2.13097	213.35399	3.03796

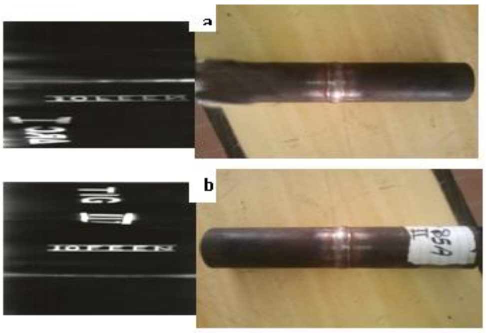


Figure 8. XRD of the pipe after welding by a) SMAW and b) GTAW techniques

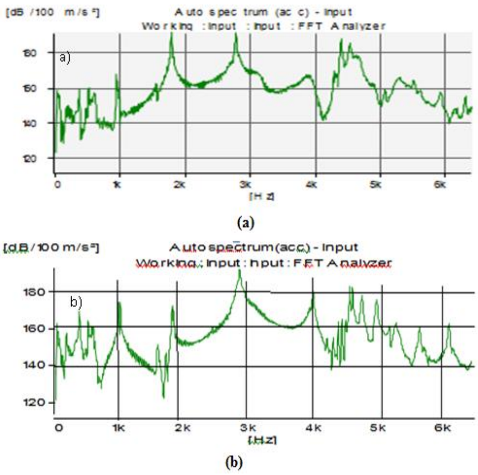


Figure 9. FRF of SMAW welding of ASTM A 106 at 85A a) without crack b) with crack

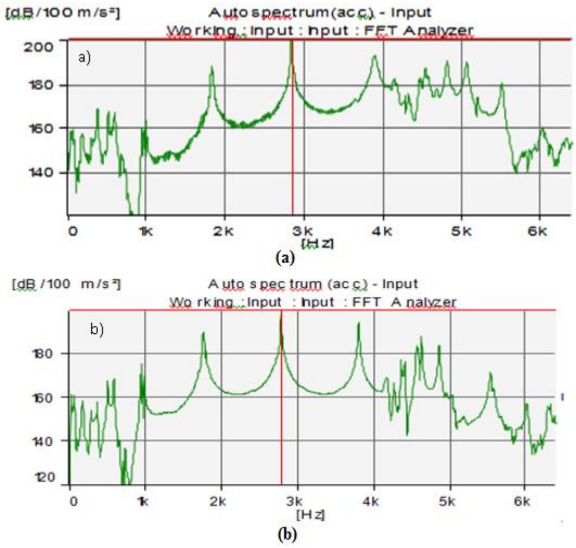


Figure 10. FRF of GTAW welding of ASTM A 85 a) without crack b) with crack

TABLE 5. The damping and frequency of GTAW technique

	Without crack		With crack	
Mode	Damped Frequency (Hz)	Damping (%)	Damped Frequency (Hz)	Damping (%)
1	13.77874	7.22431	11.81685	6.56943
2	27.14170	5.95831	26.24580	4.75843
3	163.52846	5.33122	154.24592	4.58965
4	236.65903	2.15763	226.65903	3.27710

4. CONCLUSIONS

The results of the present study can be concluded in the following points:

- The peak loads in the three point bending (3PB) test are higher in case of SMAW as compared with GTAW. This effect can be attributed to the higher heat input in the latter due to the slower welding speed. Both welded and non-welded pipes give almost the same peak loads in 3PB tests which signify the good welding practice.
- In SMAW, the higher the welding current the lower will lie the peak loads as well as the buckling loads. Also, the yield strength and the ultimate tensile loads for GTAW are relatively higher (34.7 KN) as compared with SMAW (33.8 KN).
- For non-cracked pipes, it was found that having the first three modes, the higher damping frequency, and the lower damping ratio. This reflects the difficulty of dissipating energy at higher frequencies. SMAW joints give higher damping ratio (7.418%) as compared with GTAW joints (7.220). So, the latter joints have higher stiffness than former ones.
- The non-welded steel pipes (ASTM A106) have shown to attain relatively high damping ratio (6.876%) as compared with welded joints (5.958 for GTAW as 6.173 for SMAW, 85A).
- For cracked pipes of GTAW, crack results in a reduction of damping from 8.110 to 6.569 %. Such an unexpected result may be attributed to the small depth of the crack (2mm) as compared with pipe thickness, almost one fourth of pipe thickness. For SMAW, crack has the same effect as in GTAW, regardless of welding current. However, cracked pipes welded lay 85 A seem to have highest damping for all the tested pipes (8.110%).

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چکیده

در کار حاضر نظارت بر سلامت ساختار (SHM) لوله‌های فولادی از طریق روش ارزیابی آسیب جوش بر مبنای ارتعاش برای تشخیص وضعیت جوش استفاده شده است. کمیت‌های پویا از قبیل عملکردهای پاسخ فرکانس (FRF)، شکل و حالت پارامترهای ارتعاش ساختاری برای شناسایی آسیب ها ، در حالت میانگین خطی با تحلیل از حداکثر ۳/۲ کیلوهرتز اندازه گیری شدند. در این پژوهش از دو روش جوشکاری یعنی: (SMAW) و (GTAW) استفاده شد، به منظور ارزیابی کیفیت جوش از آزمون‌های ایستا استفاده شد. این آزمون‌ها خم کردن سه نقطه‌ای، خم کردن سطحی، و کشش محوری بودند. به علاوه، عکس برداری با پرتو ایکس به عنوان یک روش NDT نیز به کار گرفته شد.

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