MODELLING AND SIMULATION OF ELASTIC & PLASTIC BEHAVIOUR OF PROPAGATING IMPACT WAVE

IMPACT- ECHO AND EXPLOSIVE WELDING PROCESS DEVELOPMENT

Mohammad Tabatabaee Ghomi

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Abstract

A force that is applied dynamically in a short period of time is called an impact force (shock wave). Due to the concentrated application of force on a small area in a fraction of a second, unique applications have emerged that other types of loadings are not capable of performing. Explosions, an impact of a hammer, impact of waves on a shore wall, or the collision of two automobiles are examples where impact waves occur. In this research the effects of impact on solid materials and the motion of stress waves due to the impact are studied and some of their industrial applications are described.

The primary objective of this work is further development of some elastic and plastic impact wave methods, aiming to reduce the energy consumption of explosive welding (EXW) as well as the cost of NDT technologies. Many numerical simulations and a vast amount of experimental work were employed to reach this goal.

The impact wave creates elastic deformations that move the particles of the body. In this research we focused on dimensional measurement by calculating the time of wave travel between the source of energy and a discontinuity in the part studied. The impact echo (IE) method can be used for determining the location and extent of all kinds of flaws, such as cracks, de-lamination, holes and de-bonding in concrete structures, columns and hollow cylinders with different cross-sections and materials. In the present study, simulation of the impact-echo method was carried out numerically using direct and indirect methods. In the direct method a steel ball directly impacts on the upper surface of a concrete plate-like structure, whereas in the indirect method the impact impulse transmits to the concrete plate via a steel bar, in order to adapt the method for situations where there is no access to the plate being measured. In each method a two-dimensional finite element analysis (in axisymmetric geometry) was performed for the thickness measurement of concrete plates using the LS-DYNA program. Numerical results are presented for different values of plate thickness and different projectile speeds for both the direct and the indirect method and the indirect results are validated by comparison with the results obtained by the direct method. The method was validated against experimental measurements.

A high energy impact wave produces plastic deformations in metals. In this research explosive welding was studied as an application of high energy impact waves. A new method for joining different, non-compatible metals (Al and Cu-based materials) was introduced. This method may be extended for use in offshore applications. Many 3-D numerical simulations were performed using the ABAQUS explicit commercial software. The model was validated against experimental measurements.

The outcome of this research work could be summarized as follows:

a) Introducing an indirect IE method in NDT technology for thickness measurement in particularly inaccessible structures.

b) Introducing a new, grooved method in EXW technology to join surfaces made of different materials, in particular Al-Cu joints.

The results could be employed to reduce the energy consumption and cost associated with EXW and IE technologies. The methodology can be used in many other applications in all kinds of process industries.
To my wife
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Svensk sammanfattning

En kraft som angriper dynamiskt på kort tid kallas en anslagsvåg (stötvåg). På grund av den på ett litet område och under en bråkdel av en sekund koncentrerade kraften, har unika tillämpningar skapats som det har visat sig att andra typer av belastningar inte kan utföra. En explosion, ett hammarslag, vågornas anslag mot en strandmur eller en collision mellan två bilar är exempel där stötvågor uppkommer. I denna forskning har effekterna av stötvågors påverkan på fasta material och rörelsen av spänningsvågor förorsakade av deras energi studerats noggrant och några av deras industriella tillämpningar beskrivs.

Det primära syftet med detta arbete är fortsatt utveckling av några elastisk-plastiska vågmetoder i syfte att minska energiförbrukningen för sprängsvetsning (EXW) och kostnaden för icke förstörande testning (NDT). Många numeriska simuleringar och en stor mängd experimentellt arbete har utförts för att nå detta mål.


Resultaten av detta forskningsarbete kan sammanfattas som:

a) Att införa en indirekt vågeco-metod (IE) för icke-förstörande tjockleksmätning i särskilt svårtillgängliga strukturer.

b) Framtagning av en ny sprängsvetsmetod utnyttjande spår i materialen för att bättre sammanfoga ytor av olika material, i synnerhet av aluminium resp. koppar.

Resultaten kan utnyttjas för att minska energiförbrukningen och kostnaderna i samband med sprängsvets- och IE-teknik. Denna metodik kan också användas i många andra tillämpningar i alla typer av processindustrier.
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M. Tabatabae

Västerås, Dec. 2011
Published papers from present thesis

Papers included in the doctoral thesis
This thesis is based on the following papers:

**Paper A:**

**Paper B:**

**Paper C:**

**Paper D:**

Other Papers not included in the doctoral thesis

**Paper E:**

**Paper F:**

**Paper G:**

**Paper H:**
Symbols

\( A \) Amplitude
\( C \) Sound speed
\( C_p, C_L, C_a, C_s, C_r \) Wave speed
\( E \) Young’s modulus
\( E_i \) Internal energy
\( E_s \) Strain energy
\( f \) Frequency
\( G \) Shear modulus
\( H \) Hardness
\( I \) Moment of inertia
\( J \) Polar moment of inertia
\( l \) Wavelength
\( P \) Pressure
\( Re \) Reynolds number
\( T \) Temperature
\( T \) Thickness
\( T \) Time
\( V \) Specific volume \((1/\rho)\)
\( V_{d}, V_{d} \) Detonation velocity
\( V_{f}, V_{f} \) Velocity of flyer plate
\( V_{s}, V_{w} \) Collision velocity
\( u, v, w \) Displacement
\( Y \) Yield stress
\( \alpha \) Initial angle
\( \beta \) Dynamic angle
\( \beta \) Shape factor
\( \sigma \) Tensile stress
\( \tau \) Shear stress
\( \varepsilon \) Strain
\( \lambda \) Wavelength
\( \rho \) Density
\( \nu \) Poisson’s ratio
\( \theta, \omega \) Angle
\( \omega \) Gruneisen parameter

Abbreviations

IE Impact-echo
NDT Non-destructive testing
EXW Explosive welding
TBS Tensile Bond Strength
WW Welding window
SEM Scanning electron microscopy
TEM Transmission electron microscopy
UTS Ultimate tensile stress
FFT Fast Fourier Transformation
PE Plastic strain
PEEQ Equivalent plastic strain
S12 Maximum shear stresses
S22 Normal stress
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Part II: Papers
Part I:

Thesis
1 Introduction

Impact waves are stress waves that produce elastic and plastic deformation. Explosive welding and explosive shaping occur in the plastic region. In comparison, ultrasonic measurement and impact-echo make use of stress waves in the elastic region. In this research two effects of the impact energy in the solid materials and the motion of stress waves due to the impact energy are studied thoroughly and some of its industrial applications are described: impact-echo in elastic and explosive welding in plastic deformation.

Elastic wave propagation application

When a stress wave travels through a solid body, different parts of that body “will be disturbed from their equilibrium” like at impact between solid bodies. This deviation from equilibrium needs “certain time” to reach the other parts of the body. The local non-equilibrium moves the particles of the object and is accompanied by a re-distribution of stress. The stresses produced translate with a certain velocity in the object in the form of a wave. By this definition there are two different velocities in the object: “the velocity of particles” and “the velocity of stress wave propagation”. It is possible that these two types of waves propagate simultaneously in the body. In the primary investigation of elastic stress waves, two types of waves are studied:

- Longitudinal stress waves
- Torsional stress waves

In this discussion, a rod is a solid body with the length of which is much greater than the dimensions of its cross-section. In a long and fixed rod, a longitudinal stress wave propagates in the two forms of pressure stress and tensile stress waves. In pressure stress waves, regardless of the Poisson's ratio, the direction of particle motion and the direction of wave propagation are the same, whereas in tensile stress waves, these two are in opposite directions. It is also to be noted that torsional stress waves move longitudinally and the particles move in the cross-section of the rod. In other words, these two directions are orthogonal to each other (Johanson, 1970).

Non-destructive tests for measuring length and in special cases for measuring thickness are used extensively in different industries for quality control in manufacturing and for diagnosing defects in repair and maintenance. One common application of measuring elastic wave propagation in solid bodies is measuring length and the thickness.

The ultrasonic method can be used at different frequencies for measuring different thicknesses. In the ultrasonic method measurement is made rapidly and with high reliability so that there is no need to access the opposite face of the part. Ultrasonic measurement is based on the propagation of sound produced by piezoelectric transducers.

The impact echo is another method for measuring thickness. This is a non-destructive test method for measuring concrete and masonry. The stress waves caused by an impact propagate inside the structure and are reflected by internal cracks and outside surfaces of the part. The impact echo method can be used for increasing the precision of the non-destructive tests verified by ASTM for measuring thickness of concrete plates (ASTM- C1381-98a).

It can also be used to determine the location and extent of flaws such as cracks, delaminations, flaws, honeycombing and debonding in plain, reinforced, and post-tensioned concrete structures. The method can be used to locate voids in grouted tendon ducts of many types of post-tensioned structures. Other notable applications of this method include determining thickness or location cracks, voids, and other defects in masonry structures where the brick or block units are bonded together with mortar. Reinforcing steel rods have no adverse effects on the results of an impact echo test.
Plastic wave propagation application

In the second type, the impact energy produces plastic deformations in metals. Explosive welding and cladding and high rate forming are among the important applications of this type of impact energy. In this research we worked on explosive welding as an important application of plastic deformations caused by impact energy. Explosive welding is one of the applications of impact mechanics. In explosive welding an oblique impact on two metal plates causes them to join the material at the interface. Because of high velocity of impact a jet is formed that cleans away the surfaces of the two impacting plates and causes the plates to be welded together. The strength of welded joint is the same as or higher than that of the weaker metal.

1.1 Background

Using impact energy comes back to many years ago, when man used a hammer for the first time. He discovered naturally the need of knocking in many of the works he had made such as weapons or swords. Scientifically the need of the science of impact mechanics comes back to the 1850s, because in mechanical calculations more than a half of the forces are dynamic forces and the science of the strength of materials mostly applies to determining static forces and could not be applied to dynamic calculations.

One of the advantages of using impact mechanics is in studying the wave propagation in solids, where it is possible to detect and evaluate the solids physically without any destruction of the part. It occurs in the elastic deformation region and is an important method of non-destructive testing (NDT). For many years people were checking metals by knocking with a hammer on the part, such as a railway carriage wheel, and listening to variations in the "ringing" sound to detect the presence of internal voids, cracks or other defects. Although the study of acoustic science has a long history, its new applications in ultrasonic waves date back to the first years of the twentieth century.

The first uses of ultrasonic waves for inspection go back to the last years of 1930s. Since their introduction in the early 1940s, the ultrasonic pulse-echo methods have been developed extensively, and have been become efficient, versatile and reliable non-destructive test method for metals, plastics, and other homogeneous materials. Apart from limited use in detecting flaws in or measuring the thickness of thin concrete members, ultrasonic methods have had little previous success in the testing of concrete, because of the high-frequency stress waves they employ (typically 100 kHz and above), which are strongly attenuated by the heterogeneous nature of this material. At the middle of the twentieth century many instruments were made and much research had been done in this field. Acoustic methods are the oldest and most widely used form of non-destructive testing. They are based on the propagation, and in some cases reflection, of stress waves in solids. Three techniques based on stress wave propagation, and differentiated by the methods used to generate and receive stress waves, have been used for evaluation of concrete. They are: 1- the through-transmission or pulse-velocity method; 2-resonance methods; and 3-echo methods (Sansalone& Streett, 1997).

In the present research work, echo method for flaw detection in concrete structures is used other than deep foundations. At the end of last century a group of researchers invented a method named impact echo for inspection of masonry and concrete, that has found extensive uses up to now. Impact-echo is an acoustic method for non-destructive evaluation of concrete and masonry, invented at the U.S. National Bureau of Standards (NBS) in the mid-1980's, and developed at Cornell University, Ithaca, New York, from 1987-1997.

Impact mechanics has extensive uses to achieve plastic deformation zones. Hammering for forging and hardening and explosive forming produce plastic deformation in solids. Explosive welding is another application of impact energy. Explosive materials were first used in manufacturing shortly after the Second World War. However, the first observation of their potential uses in manufacturing
dates back to World War I. It had been observed that a bullet did not only pierce metal but could also be welded to it. This phenomenon was subsequently reproduced in the laboratory and applied commercially in industry. Advances in the aerospace industry and the close tolerances necessary for manufacturing complex parts drove the use of the EXW method at an industrial scale. By the mid-1950s, EXW was being applied in manufacturing.

In the following years, it was quickly accepted that EXW methods could be applied to some other industries. EXW processes were adapted and refined to serve the needs of the automotive, shipbuilding, material processing, mining, and construction industries, among others. Over three hundred types of joints between similar and dissimilar materials have been produced until now. The first experiments with the EXW technique were carried out on flat surfaces, but many commercial tests have been subsequently done on curved surfaces such as pipelines and heat exchanger components.

1.2 Literature review

In this section previous research works have been categorized in to three interrelated sections as, stress waves, elastic waves and plastic waves for EXW applications.

Stress waves
The basic theory are well developed in a myriad of text: On the general analysis on elastic wave propagation in solids, analytical, computational, and experimental techniques have been reviewed by Love(1906); Kolsky(1963); Lur’ e (1965); Fedorov (1968); Achenbach(1973); Wasley(1973); Timoshenko & Goodier(1973); Keith & Crampin (1977); Hudson(1980); Aki & Richards (1980). During the completion of this thesis work, some text books covering the fundamentals of wave propagation have frequently been consulted: “Impact strength of materials” by Johanson (1970), “Fundamental of seismic wave propagation” by Chapman (2004) and “wave propagation” Notes by Mei(2006).

Using the above-mentioned works, an extensive study on the behaviour of waves in solids can be performed.

Elastic waves for inspection uses
In the next step, I reviewed some books and papers in the field of ultrasonic measurement (Glickstein, 1960); (Blitz & Simpson, 1996); (Popovics, Gibson & Gallo, 2005); (Blitz, 1971) and also some resources about the piezoelectric sensors (Phillips, 2000); (Prokic et al., 2001); (Tong et al., 2002), and the new method was discovered in the last decades named Impact-Echo (IE). The IE method has been used for more than a decade for non-destructive testing (NDT) of concrete structures. Its applications are multifaceted and on concrete elements they include the location of voids, faults, delaminations as well as the thickness (Sansalone et al., 1998) determination of single and multilayer structural components (Lin & Sansalone, 1997); (Poston & Sansalone, 1997); (Sansalone, 1997); (Jaeger et al., 1996,97); (Sansalone & Streett, 1997); (Lin & Sansalone, 1992-96); (Cheng & Sansalone, 1993,98); (Pratt & Sansalone, 1992); (Sansalone & Poston, 1992); (Carino & Sansalone, 1992,98); (Lin et al., 1990,91); (Sansalone et al.,1987,90,91); (Sansalone & Carino, 1987-91); (Carino et al.,1986); (Pessiki & Carino, 1987) and finally were reviewed other papers about the impact echo especially about simulation fields (Sansalone & Carino, 1986); (Carino & Sansalone, 1984);(Carino et al., 1986); (Stavroulakis, 1999); (Kima et al., 2002); (Schubert et al., 2004); (Colla & Lausch, 2003); (Popovics et al., 2005); (Chiamen et al., 2008); (Liu & Yeh, 2010) Most of them are used in masonry or concrete inspections. In all of these works, a direct contact between the impacting object and the part has been applied. By studying these papers, it is possible to select the correct set of simulation methods and modelling parameters.
Plastic waves for EXW uses

In the third section were reviewed the most studied works about plastic waves for explosive welding methods.

Major reference works in this field are the book by El-Sobky & Blazynski (1983). In this book, they described clearly the method of explosive welding, explained wave phenomena and the overall EXW procedure. The basic method is also described in the book by Crossland (1982). The PATON Institute (PATON, 2002); professor Darvizeh (1998); professor Liaghat (2000) have performed many EXW experiments. The fundamentals of the EXW process have been explained in a number of handbooks (ASM&SME, 1983). The mechanism of wave interference has also been described in the literature (Chemin, 1989); (Onzawa et al., 1985). A number of scientists considers EXW to be essentially a fusion welding process (Phillipchuk, 1961) which relies on the kinetic energy at the interface. Williams & Crossland (1970) looks at the process as a pressure welding method.

Otto and Carpenter (1973) offered that interfacial shear occurs during welding, and attributed the weld to the result of heat generated by shearing at the boundary. The process reaches a very high temperature at the interface, exceeding the melting point of the welded parts, for a short period of the order of microseconds. Onzawa (1985) reached a similar conclusion in his study. He achieved interface observations using transmission electron microscopy (TEM). It is generally believed, based on experimental data, that jet creation makes an essential contribution to welding. The jet cleans the surfaces by removing a thin layer of metal oxides and other pollutants. The analytical solutions of the pressure and jet velocity of the impact of liquid drops were found by Lesser (1981) and Lesser & Field (1983), provided the first photographic indication of the result.

Wilson & Brunton (1970) studied the waves that form in the interface. The theories suggested for the mechanism of the wave formation can be classified as indentation mechanism, vortex shedding mechanism, flow unsteadiness mechanism and stress wave mechanism (Reid, 1974). Bahrani & Crossland (1964) and Abrahamson (1961) have worked on groups of these categories. Another theory of wave formation was proposed by Hunt (1968) who suggested that the explosive welding wave forms when there is a velocity difference between adjacent streams.

The flow instability mechanism was described by Robinson (1975), who suggested that the waves are created behind the collision zone because of a velocity through the interface which contains a jet. Cowan (1971); Kowalick & Hay (1971) who pointed out the parallels between the waves in explosive welding and the Von Karman’s vortex street generated by a barrier. A stress wave mechanism of wave formation was suggested by El-Sobky & Blazynski (1975). This wave formation mechanism was recognized by Plaksin et al. (2003). A practical book was written by Neubauer et al. (1988).

The Explomet conferences, organised from 1980 until 2000, every five years, contain much material on Explosive Welding from, among others, University of California, San Diego, Los Alamos and Sandia National Laboratories. Most of them were published in book form much later than the conference years (Meyers et al., 1992, 2001).

Lazari and Al-Hassani (1984) studied the behaviour of metal plates under explosive stress using a finite element method. They used the theory of virtual displacement of the Lagrangian deformation to develop the equations of motion. Oberg et al. (1984) simulated the explosive welding process using Lagrangian finite difference computer code. The process was also modelled by Akihisa (1997). Finally, the results of simulation provided by Al-Hassani & Akbari Mousavi (2005, 2008) have been reviewed.

In all of these research works, the explosive welding was studied and simulated in co-planar surfaces. By a comprehensive study of the papers, simulation method and modelling the parameters has been selected.
Frontiers of knowledge and technology
Use of waves for inspection and measurement has been under study for more than two decades. This topic is a widespread area of research and can be used in materials, parts and assemblies in various situations. Professor Sansalone and her research team in the US (Sansalone et al.) have been working on this method for about 20 years and could provide many useful applications for industry. The method uses the equations of motion, reflection of waves and the equation of waves and is suitable for applying simulation tools for solving the equations and modelling the processes. In spite of the amount of work done to improve this method, there are plenty of opportunities for finding new applications and improvements, especially in the field of measuring lengths in situations where there is not enough access to the physical surfaces to be measured.

Explosive welding is a wide area of research and serves as a unique method to produce special welded joints that are not possible to make by other welding technologies. In the last three decades, many research works were conducted on explosive welding. A research project at the University of Manchester under the supervision of Professor Al-Hassani (1984-2005) was carried out quite significant on the explosive welding technology and its applications. In this method the equations of motion are used to describe the processes. Due to the difficulties that exist in the arrangement of experiments by explosive materials, simulation tools can be a great assistance in understanding the overall process. In the explosive welding of two unequal surfaces, the following concepts must be taken in to account, discontinuity between edges, and the reflection of waves from the edges which can cause changes in the impact conditions, leading to poor quality welds or un-welded areas near edges. Since a little amount of experimental work has been conducted on this part, the present work can further enhance this part of the research on explosive welding technology.

1.3 Motivation

- Application of the impact wave energy in industry is the main motivation. The southern Iranian aluminium company ALMAHDI had a requirement for special copper-aluminium joints with unequal surface areas. Joints they had made previously were unsatisfactory. As a result of this thesis, more than 1000 successful EXW joints have been made and confirmed by the factory. Another motivation for conducting this thesis was the problems faced by the oil and gas industry in repairing and preventing leakage in pipelines.

When I was studying on the application of the impact echo method for testing concrete tanks in a research organization, it was noticed the huge amount of soil excavation was needed to provide access to the tanks. It was thought that if it is possible to measure the thickness of concrete tank indirectly it would mean a great improvement.

Noting that these two subjects were related to the impact energy topic, it was decided to work on them under the title of the impact energy and focus on the development of the current methods. Thus, I could find new applications for impact waves using modelling and simulation techniques and became interested in working on different areas of this topic.

1.4 Goals, objectives and expected results

The primary objective is further development in process of the elastic and plastic impact wave methods. This has been done through:

- Introducing an indirect IE method in NDT technology for thickness measurement of inaccessible structures and in particular in underground or offshore applications
Introducing a new grooved method in EXW technology subjected to non-equal surfaces and in particular Al-Cu joint application.

The ultimate goal is to reduce the energy consumption of the EXW technology as well as cost reduction associated with NDT technology. The methodology can be used in many other applications in all kind of process industries. A load of numerical simulations together with careful experimental work has been employed to reach this goal.

**The secondary objectives**

The secondary objectives are as below:

- Deep understanding of the IE and EXW technologies
- Modelling and simulation of the IE and EXW methods to analyse the effect of the operation parameters on the process
- Cost and energy reduction in elastic and plastic wave impact process
- To document the methodology and take it a significant step forward aiming to generalize it for further use in many other different industrial process applications

**Expected Results**

The expected results are as below:

- Reduction of energy consumption due to applying a new method of EXW Al-Cu joining in the aluminium factory
- Reduction of cost as a result of employing a new method of indirect inspection
- Development of new methods in EXW and IE processes from a scientific point of view
- Deep understanding of the effect of reflection of the impact wave on EXW and IE applications
- Modelling and simulation of unequal surfaces for explosive welding and to study scientific research on the edges of joints
- Patent applications on new methods of impact echo and explosive welding will be filed

**R&D challenges**

R&D challenges could be written as below:

**Question 1**

- How the impact echo method can be used to indirectly measure the thickness of concrete or metal tanks and pipes in cases where there is not direct access to the surfaces to be measured? How the validity of the obtained results can be evaluated by direct measurement methods?

**Question 2**

- The impact echo experiments need related instruments including sensors, computers and special software. What use can we make of simulation techniques to reduce the cost of experiments?

**Question 3**

- What is the effect of reflection of waves on the precision of the experiments?

**Question 4**

- In the explosive welding method, can we use the energy of the reflected waves to remove the discontinuity of a welded joint at the edges when we join non-equal surfaces?

**Question 5**

- Regarding the costly and dangerous nature of the explosive welding experiments, how can we use modelling and simulation tools to reduce these undesired factors?

**Question 6**

- The initial settings of explosive welding experiments are very difficult and dangerous. The explosive welding process is a multidisciplinary subject that touches many engineering
disciplines. The calculation of effective parameters is mostly done on an experimental basis and the results of simulation may differ greatly from the actual situation. Noting these facts, how can the simulation model be verified and what are the actual arrangements of the tests?

Limitations
In impact measurement, the most important limitation is reflection of the lateral waves from the surfaces. This phenomenon reduces the accuracy of measuring.

In explosive welding, working with explosives can be very dangerous and the high levels of sound produced can be harmful to hearing. Reflection of waves reduces the strength of welding at the edges.

1.5 Research methodology

The work described by this thesis includes studies of the process, review of previous work in the field, design of experiments using different materials and shapes, manipulation and control of parameters before and after experiments, calculation of the parameters, process development, simulation and comparison of the results with famous software such as LS-DYNA and ABAQUS, introducing the applications and commercialization after improving the results.

Finally the results will be published as a paper or filed as patents. The research and experiments described in this thesis are divided into two applied fields as;

a) Using impact energy for measurement in elastic area.
b) Using impact energy for explosive welding in plastic area.

The research program chart is shown in Fig. 1-1 and the work division flowchart is summarized in Fig.1-2.
In theory, the sheet is considered infinite for removing the limitation of impact measurement. However, our work has an industrial nature and we work actually on finite surface plates. We minimize the adverse effects of the reflection of waves by using simulation techniques and choosing the correct arrangement for the tests.

In explosive welding the experiments for the thesis were performed in a vacuum chamber. By introducing a new idea and using simulation techniques and results of actual experiments, we reduce reflection problem significantly to reach an acceptable degree.

### 1.6 Contributions of this thesis

The main contributions of the present thesis can be summarized as follows:

- Modelling and simulation of impact-echo method and introducing a new indirect method
- Introducing a new solution for measuring the thickness of steel plate in impact-echo
- Investigation and simulation for reflection of waves in IE and edge problem in EXW
- Introducing a new Grooved method for unequal surface in EXW
- Reducing energy consumption and process development in an AL-CU joint
The main contributions of the paper included in this thesis can be summed up according to the research questions that are most related to:

**Question 1:** How the impact echo method can be used to indirectly measure the thickness of concrete or metal tanks and pipes in cases where there is not direct access to the surfaces to be measured?

**Question 2:** What use can we make of simulation techniques to reduce the cost of experiments?

**Question 3:** What is the effect of reflection of waves on the precision of the experiments?

**Paper A: Concrete Plate Thickness Measurement Using the Indirect Impact-Echo Method**

The impact-echo method has been used for non-destructive testing of concrete structures since its introduction more than two decades ago. This method has multifaceted applications on concrete elements including the location of voids, faults and delimitation. The thickness of single and multilayer structural components can also be determined using this approach. In the present study, a simulation of the impact-echo method was carried out numerically using direct and indirect methods. In the direct method, steel ball acts as an impacting object and directly exerts impact on the upper surface of a concrete plate-like structure. In the indirect method, the impact impulse is transmitted to the concrete plate via a steel bar. Each method uses a two-dimensional finite element analysis, referred to as a LS-DYNA program, to measure the thickness of concrete plates. Numerical results are presented for different values of plate thickness and different projectile speeds for both the direct and indirect methods. The indirect results were validated by comparing them with the results from the direct method. The results indicate that the impact response of a concrete plate for a dominant thickness frequency using an indirect impacting object agrees with the direct impact method and that these responses correlate with the actual plate thickness. The behaviour of stress waves in the steel bar was investigated and is consistent with the previous theoretical and experimental studies.

**Paper B: Steel Plate Thickness Measurement Using Impact-Echo Method**

The impact echo method is usually used for concrete structures. In this study we applied it for steel plates and the results indicated that this method also could report truly the thickness of the steel plates. In the present study, the simulation of the impact-echo method was carried out for the first time on a steel plate. Numerical results are presented for different values of plate thickness and different projectile speeds and the obtained results are validated by comparing them with the results reported in the available literature that have applied the IE method for concrete plates and actual thicknesses.

**Question 4:** Can we use the energy of the reflected waves to remove the discontinuity of a welded joint at the edges when we join non-equal surfaces in EXW method?

**Question 5:** How can we use modelling and simulation tools to reduce the undesired factors?

**Question 6:** How can the simulation model be verified and what are the actual arrangements of the tests?

**Paper C: Explosive Welding of Unequal Surface using Groove Method**

This paper describes studies on impact waves and designs a new applied technique for removing the strength problem at the edges of Al-Cu welded plates to obtain a uniform weld. Tensile Bond Strength of welded joints is an important factor in the explosive welding process. In such welding process, stress waves produced by explosive energy propagate at the free surface and produce tension
stresses. These waves result in spalling or scabbing at the edges of metals. These phenomena reduce the Tensile Bond Strength (TBS) of explosive welding, and the most common method for solving this problem is cutting and sizing the edges. However, this is not possible when the two metal parts to be joined are of different sizes. This paper focuses on applying a new technique (Groove Method) for solving the strength problem at the edges due to obtain uniform welding. In this way, experimental and numerical analysis is performed to evaluate the Groove Method. Numerical results are in good agreement with those of experiments. The obtained results show the success and effectiveness of the groove method suggested in this paper. The results are validated by tensile experiments and simulation software. This method is suggested for explosive welding in metals with unequal surface areas. Results of this research are applied in an aluminium Company.

**Paper D: Finite element simulation of explosive welding**

Explosive welding or bonding is a solid-state welding process that is used for the metallurgical joining of dissimilar metals. The process uses the forces of controlled detonations to accelerate one metal plate into another creating an atomic bond. Explosion bonding can introduce thin, diffusion inhibiting interlayers such as tantalum and titanium, which allow conventional weld-up installation. This paper describes work carried out to numerically analyse a two plate welding process using a finite element method (FEM) and the verification of the results using experimental data. The numerical simulations identify factors such as the level of strain induced in the plates and the direction of the shear stress at the collision zone at the surface of flyer plates as indicators of Tensile Bond Strength.

**Paper E: Removing Leakage from oil and gas low pressure pipes by explosive welding method**

Explosive welding occurs under high velocity oblique impact, and it is possible to use explosive energy to form a conventional cold pressure weld. One of the advantages of this method is that it can be used to weld different materials with different shapes. Explosive welding can be used for the maintenance of pipes and vessels, in repairing leaks especially in under water pipes in the oil and gas industries. We describe a new explosive welding method for repairing leaks in metal pipes that is very economical and easy to apply.
2 Theory

2.1 Elastic impact waves: Impact-echo

2.1.1 Different types of waves

Different types of waves can be propagated in the solids. In longitudinal or compressive waves (P-waves) the direction of particle motion is along the direction of wave propagation (Fig.2-1a). The second type is the shear waves (S-Waves), which propagate perpendicular to the direction of particle motion (Fig.2-1b). It is possible to produce surface waves, that that are called surface or Rayleigh waves. These three types of waves can be propagated in solids, but shear waves cannot propagate in liquids and gases.

\[ l = \frac{v}{f} \]  

(2.1)

Where \( l \) is the wavelength, \( v \) is the wave speed and \( f \) is the wave frequency.

2.1.2 Propagation of elastic waves

Elastic wave propagation in a thin plate

In a thin and uniform plate at the plane stress state two elastic waves propagate. The equations of motion could be written according to Fig.2-2:

\[ \rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} \]  

(2.2a)

\[ \rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} \]  

(2.2b)
The stress-strain relationships for the elements in an isotropic material are:

\[
\varepsilon_x = \frac{\partial u}{\partial x} = \frac{1}{E} \left( \sigma_x - v \sigma_y \right) \tag{2.3a}
\]

\[
\varepsilon_y = \frac{\partial u}{\partial y} = \frac{1}{E} \left( \sigma_y - v \sigma_x \right) \tag{2.3b}
\]

\[
\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\sigma_{xy}}{G} \tag{2.3c}
\]

We can write these equations in the following form:

\[
\sigma_x = \frac{E}{(1-v^2)} \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) \tag{2.4a}
\]

\[
\sigma_y = \frac{E}{(1-v^2)} \left( v \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right) \tag{2.4b}
\]

\[
\sigma_{xy} = G \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \tag{2.4c}
\]

According to equations (2.2) and (2.4):

\[
\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho (1-v^2)} \frac{\partial^2 u}{\partial x^2} \tag{2.5a}
\]

\[
\frac{\partial^2 v}{\partial t^2} = \frac{G}{\rho} \frac{\partial^2 v}{\partial x^2} \tag{2.5b}
\]

Thus there are in general two wave speeds in the plane of the plate; one causes displacements parallel to the translational axis and has a value of \( C_L = \frac{E}{\rho (1-v^2)} \) and the other which causes displacements transversely to the axis has a speed \( C_T = \frac{G}{\rho} \).

### Surface and Rayleigh waves

In an isotropic material for a given direction there are two wave speeds \( c_t \) and \( c_L \), but when the body has free surfaces, other types of waves may be formed. There are surface waves; a simple example is a surface sea wave. It was shown by Rayleigh in 1887 (Viktorov, 1967) for the first time, and then earthquake studies confirmed the occurrence of this type of wave. For \( v=0.25, c_s = 0.92 c_t \), and for \( v=0.5, c_s = 0.96 c_t \) (Johanson,1970), where \( c_s \) is surface speed. The amplitudes of waves decrease...
rapidly, exponentially, so that at depth below the surface, the speed is always less than $c_t$. A surface wave is also denoted as a Rayleigh wave (R-wave).

**Propagation of a short pulse through a short cylinder**
Kolsky (1963) has demonstrated that the propagation of a wave through a short cylinder is complex. A small explosive charge was used to produce a pulse at the centre of end face of a steel cylinder, the pulse duration being about 2μs. Both P and S waves were created by the explosive charge and spread out spherically from it. Waves travelled by a number of paths of different lengths (See Fig. 2-3).

![Fig. 2-3: Propagation of a wave through a short cylinder (Johanson, 1970)](image)

**Propagation of a compressive pulse**
Fig.2-4 shows an element of a rod in which is transmitted a longitudinal compressive wave, and $u$ denotes the displacement at a plane AB, and then $u + \frac{\partial u}{\partial x}$ denotes the displacement of plane $A'B'$. The net force on element $A'B'B'A$ causes it to accelerate so that the equation of motion of the rod of initial cross-sectional area $A_0$ and density $\rho_0$ could be written as:

$$-\frac{\partial \sigma_0}{\partial x}, A_0 = A_0 \rho_0 \frac{\partial^2 u}{\partial x^2}$$

(2.6)

So:

$$\frac{\partial \sigma_0}{\partial x} = -\rho_0 \frac{\partial^2 u}{\partial x^2}$$

(2.7)

![Fig. 2-4: The net force on an element (Johanson, 1970)](image)
Hooke’s law is:
\[
\frac{\partial u}{\partial x} = -\frac{\sigma_x}{E}
\]  \hspace{1cm} (2.8)

Where \(E\) is the Young’s modulus of elasticity.

By combining the above equations we can obtain the following differential equation:
\[
\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho_0} \frac{\partial^2 u}{\partial x^2} = C_L^2 \frac{\partial^2 u}{\partial x^2}
\]  \hspace{1cm} (2.9)

Where
\[
C_L = \sqrt{\frac{E}{\rho_0}}
\]  \hspace{1cm} (2.10)

**Elastic longitudinal wave speed**

In equation (2.10) \(C_L\) is the speed of a longitudinal elastic pulse of tension or compression in an unstrained bar, and depends on the physical properties but does not depend on the shape of force. Since \(E\) is dependent on temperature, therefore \(C_L\) is dependent on temperature too. Some elastic longitudinal wave speeds for isotropic material are given in Table 2-1.

<table>
<thead>
<tr>
<th></th>
<th>Cast Iron</th>
<th>Carbon steel</th>
<th>Brass</th>
<th>Copper</th>
<th>Lead</th>
<th>Aluminium</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E) [GPa]</td>
<td>114</td>
<td>204</td>
<td>93.3</td>
<td>114</td>
<td>17.6</td>
<td>69</td>
<td>55</td>
</tr>
<tr>
<td>(\rho_0) [Kg/m^3]</td>
<td>7200</td>
<td>7750</td>
<td>8300</td>
<td>8870</td>
<td>11300</td>
<td>2660</td>
<td>1870</td>
</tr>
<tr>
<td>(C_L) [m/s]</td>
<td>3980</td>
<td>5150</td>
<td>3360</td>
<td>3690</td>
<td>1190</td>
<td>5100</td>
<td>5340</td>
</tr>
</tbody>
</table>

**Wave transmission along a bar under conditions of plane strain**

In a bar the length of which is much greater than the width the equation of motion for an element, at time \(t\) is:
\[
\frac{\partial \sigma_x}{\partial x} = -\rho_0 \frac{\partial^2 u}{\partial t^2}
\]  \hspace{1cm} (2.11)

Where \(u\) is the displacement of a particle in Fig.2-5.
Now this element is, by definition, elastically stressed under conditions of plane strain, and there is no expansion in Oz-direction, so we have $\varepsilon_z = 0, \sigma_y = 0$, or we can say the bar is free in y direction, and thus we have strain $\varepsilon_z = \frac{-\sigma_y - \nu \sigma_x}{E} = 0$, where $\nu$ is Poisson’s ratio. Thus $\sigma_x = -\nu \sigma_x$, also by using Hooke’s law,

$$\varepsilon_x = \frac{-\sigma_y - \nu \sigma_y - \nu \sigma_x}{E} = \frac{-\sigma_y + \nu \nu \sigma_x}{E}$$  \hspace{1cm} (2.12a)

$$\frac{\partial u}{\partial x} = \frac{(1-\nu^2)}{E} \sigma_x$$  \hspace{1cm} (2.12b)

Therefore, wave stress equation is:

$$\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho_0(1-\nu^2)} \frac{\partial^2 u}{\partial x^2}$$  \hspace{1cm} (2.13)

And so, the longitudinal wave speed in this state is:

$$c_L' = \sqrt{\frac{E}{\rho_0(1-\nu^2)}}$$  \hspace{1cm} (2.14)

$$\frac{c_L'}{c_L} = \sqrt{\frac{1}{1-\nu^2}}$$  \hspace{1cm} (2.15)

**Wave transmission in a bar with zero transverse deformation**

For a transverse stress and no deformation in z and y directions, therefore, $\varepsilon_y = \varepsilon_z = 0$, $\sigma_y = \sigma_z$ from symmetry, and then Hooke’s law becomes (Johanson, 1970):

$$E\varepsilon_y = \sigma_y - \nu(\sigma_y - \sigma_x) = \sigma_y(1 - \nu) + \nu \sigma_x$$  \hspace{1cm} (2.16a)

For zero transverse strain $\varepsilon_y = 0$ and thus

$$\sigma_y = \frac{-\nu \sigma_x}{1-\nu}$$  \hspace{1cm} (2.16b)

Further,

$$\varepsilon_x = \frac{-\sigma_y - 2\nu \sigma_y}{E}$$  \hspace{1cm} (2.16c)
\[ e_x = \frac{\partial u}{\partial x} = -\sigma_x \frac{(1-v-2v^2)}{E(1-v)} \]  

(2.16d)

Therefore, final wave stress equation is:

\[ \frac{\partial^2 u}{\partial t^2} = E \frac{(1-v)}{\rho_0 (1+v)(1-2v)} \frac{\partial^2 u}{\partial x^2} \]  

(2.17)

And so, longitudinal wave speed in this state is:

\[ C_L = \sqrt{\frac{E}{\rho_0 (1+v)(1-2v)}} \]  

(2.18)

\[ \frac{C_L^*}{C_L} = \sqrt{\frac{(1-v)}{(1+v)(1-2v)}} \]  

(2.19)

Or:

\[ C_L^* = \sqrt{\frac{\lambda+2\mu}{\rho_0}} \]  

(2.20)

**Reflection of stress waves**

When a longitudinal wave reaches the end of a bar, it is reflected in different states according to the boundary conditions. For a free end a tension stress wave will reflect as a compressive wave, and a compressive stress wave will be reflected as a tension wave. For a stiffly fixed end a tension stress wave will be reflected as a tension wave and a compressive stress wave will be reflected as a compressive wave (Sansalone & Streett, 1997).

At a solid/air interface nearly all of the energy in an incident wave is reflected and we were not concerned with refraction of waves into the air. However at an interface between two solid media, stress waves are partially reflected from the interface and partially refracted (transmitted) through the interface. For simplicity we will limit our attention to the behaviour of a P-wave incident upon a perfectly bonded interface between two different solid media when the direction of propagation is normal to the interface. In this case the amplitudes of the reflected and refracted waves depend upon the relative difference in acoustic impedances between the two regions separated by the interface. The amplitudes of the reflected and refracted p-wave are given by (Sansalone & Streett, 1997):

\[ A_{\text{Reflected}} = A_i \frac{Z_2-Z_1}{Z_2+Z_1} \]  

(2.21)

\[ A_{\text{Reflected}} = A_i \frac{(2Z_2)}{Z_2+Z_1} \]  

(2.22)

Where \( Z_1 \) is the acoustic impedance of the region in which the wave is approaching the interface, \( Z_2 \) is the acoustic impedance of the region beyond the interface, and \( A_i \) is the amplitude of particle motion in the incident wave. The ratio \( A_{\text{Reflected}} / A_i \) is the coefficient of reflection, \( R \),

\[ R = \frac{A_{\text{Reflected}}}{A_i} = \frac{Z_2-Z_1}{Z_2+Z_1} \]  

(2.23)
Table 2-2 shows Z-values for some materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific acoustic impedance [kg/m²s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.4</td>
</tr>
<tr>
<td>Water</td>
<td>0.5×10⁶</td>
</tr>
<tr>
<td>Soil</td>
<td>0.3 to 4×10⁶</td>
</tr>
<tr>
<td>Concrete</td>
<td>7 to 10×10⁶</td>
</tr>
<tr>
<td>Steel</td>
<td>47×10⁶</td>
</tr>
</tbody>
</table>

Thus, when a stress wave travelling through concrete encounters an interface with air, there is almost total reflection at the interface and this is why NDT methods based on stress wave propagation have proven to be successful for locating defects within solids.

The reflection coefficient given by equation (2.23) can be negative or positive depending on the relative values of the acoustic impedances of the two materials. If $Z_2 < Z_1$, such as what would occur at a concrete-air interface, the reflection coefficient is negative. This means that the sign of the stress in the reflected wave is opposite to the sign of the stress in the incident wave. Thus an incident P-wave with a compressive stress would reflect as a P-wave with a tensile stress. If $Z_2 > Z_1$, the reflection coefficient is positive and there is no change in the sign of the stress. In this case, an incident P-wave with compressive stress would reflect back a wave with compressive stress. These differences are important in distinguishing between reflections from a concrete-air interface and from a concrete-steel interface (Sansalone & Streett, 1997). Fig. 2-6 shows the phase changes in reflected p-waves.

![Fig.2-6: Phase changes in reflected p-waves (Sansalone & Streett,1997)](image)

2.1.3 Impact-Echo

**Introduction**

Knocking an object with a hammer is one of the first methods of non-destructive testing based on impact wave propagation. The method depends on the experience of the operator, and it is limited to detecting near surface defects. Depending on whether the result is a low frequency sound, or a high-pitched sound, the integrity of the member can be measured. Despite these limitations, sounding is a suitable method for sensing de-laminations, and it has been standardized by ASTM.

In non-destructive testing, the ultrasonic pulse-echo (UP-E) method has established to be a reliable method for detecting cracks and other internal faults. A transducer is used to produce a short pulse of ultrasonic waves that transmits into the object being checked. Reflection of the stress pulse happens at boundaries splitting materials with different elastic properties and densities. The reflected pulse
travels back to the transducer that also doings as a receiver. The received signal is showed on an oscilloscope, and the round trip travel time of the pulse is measured automatically. By knowing the speed of the stress wave, the distance to the reflecting interface can be determined.

Efforts to use UP-E tools designed for metal check to test concrete have been ineffective because of the various nature of concrete. The existence of paste-aggregate interfaces, air voids, and the presence of steel reinforcing bars result in a multitude of echoes that obscure those from real faults. In the last 30 years, however, there has been considerable progress in the development of useful techniques based on the propagation of lower frequency waves resulting from mechanical impact named impact echo method. This section reviews the basic concepts of stress-wave propagation including the impact echo method (Sansalone & Streett, 1997).

**Basic relationships**

When a disorder is applied suddenly at a point on the surface of a solid, such as by an impact, the disorder propagates through the solid as three different types of stress waves: P-wave, S-wave, and R-wave, with different speeds respectively. As shown in Fig. 2-7a, the P-wave and S-wave propagate into the solid along spherical wave fronts. The P-wave is related with the propagation of normal stress and the S-wave is related with shear stress. In addition, there is an R-wave that travels along the surface.

![Stress waves caused by impact in a concrete plate](image)

**Fig. 2-7**: Stress waves caused by impact in a concrete plate

(a) Stress waves at a point on the surface, b) Finite element simulation (Sansalone & Streett, 1997)

Fig. 2-7b shows the result of a finite-element analysis of the impact reaction of a plate. The figure is a plot of the nodal displacements of the finite element mesh. At this point in the analysis the S-wave is incoming at the bottom of the plate and the P-wave reflection is about halfway up the plate. In an infinite isotropic, elastic solid, the P-wave speed, $C_p$, is related to Young’s modulus of elasticity $E$, Poisson’s ratio $\nu$, and the material density $\rho$, as follows (Sansalone & Streett, 1997):

$$C_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$  \hspace{1cm} (2.24)

The S-wave propagates at a slower speed, $C_s$, given by:

$$C_s = \frac{G}{\rho} = \frac{E}{\rho(1+\nu)}$$  \hspace{1cm} (2.25)

where $G$ = the shear modulus of elasticity.

The ratio of S-wave speed to P-wave speed depends on Poisson’s ratio as follows:

$$\frac{C_s}{C_p} = \sqrt{\frac{1-2\nu}{2(1-\nu)}}$$  \hspace{1cm} (2.26)
For a Poisson’s ratio of 0.2, which is typical of concrete, this ratio equals 0.61. The ratio of the R-wave speed, $C_r$, to the S-wave speed is given by the following approximate formula:

$$\frac{C_r}{C_s} = \frac{0.87 + 1.12\nu}{1 + \nu}$$

(2.27)

For Poisson’s ratio equal to 0.2, the R-wave speed is 92% of the S-wave speed.

**Impact-echo method**

The highest success in the practical application of stress wave techniques for flaw detection in concrete has been to use mechanical impact to produce the stress pulse. Impact produces a high-energy pulse that can enter deep into concrete. The first successful applications of impact methods occurred in geotechnical engineering to evaluate the reliability of concrete piles (Sansalone & Poston, 1992). The method became known as the *sonic-echo* method. The long length of these structures allowed enough time separation between the generation of the impact and the echo arrival, and determination of round-trip travel times was quite simple. The impact reply of thin concrete members, such as slabs, is more difficult than that of long slight members. Work by Sansalone & Carino (1987-91), however, led to the development of the *impact-echo method*, which has confirmed to be a powerful method for flaw detection in thin concrete structures.

![Fig. 2-8: The impact-echo method: Mechanical impact is used to generate stress waves and a receiver next to the impact point measures the resulting surface motion (Sansalone & Streett, 1997)](image)

Figure 2-8 is a schematic drawing of an impact-echo test on a plate with a big air void below the surface. As was discussed, impact on the surface produces P- and S-waves that travel into the plate and a surface wave (R-wave) that travels away from the impact point. The P- and S-waves are reflected by internal defects or external boundaries. When the echoes or reflected waves, return to the surface, they produce displacements that are measured by a receiving transducer. If the transducer is located near to the impact point, the response is dominated by P-wave echoes. The right hand side of Fig. 2-8 shows the shape of surface displacements that would be occur. The large displacement at the beginning of the waveform is initiated by the R-wave, and the series of repeating downward displacements of lower amplitude are due to the arrival of the P-wave.

**Frequency analysis**

In the first work leading to the impact-echo method, time domain analysis was used to measure the time from the start of the impact point to the arrival of the P-wave echo. While this was possible, the process was time consuming and required skill to correctly recognise the time of P-wave arrival. A key improvement leading to the success of the impact-echo method was the use of frequency analysis instead of time domain analysis of the documented waveforms (Sansalone & Poston, 1992).
The method of frequency analysis is illustrated in Fig. 2-9. The P-wave produced by the impact reflections between the test surface and the reflecting interface. Each time the P-wave arrives at the test surface, it causes a specific displacement. Thus the waveform has a periodic design that depends on the round-trip travel distance of the P-wave.

If the receiver is near to the impact point, the round trip travel distance is $2T$, where $T$ is the distance between the test surface and reflecting interface. As shown in Fig 2-9, the time interval between the multiply reflected P-wave is the travel distance divided by the wave speed. The frequency, $f$, of the P-wave arrival is the inverse of the time interval and is given by the approximate relationship:

$$f = \frac{C_{pp}}{2T}$$

(2.28)

Where $C_{pp}$ is the P-wave speed through the thickness of the plate, $T$ is the depth of the reflecting interface. Equation (2.28) is called the plate thickness frequency and it is the basic relationship for understanding the results of impact-echo tests.

In the early research, it was assumed that the wave speed across the thickness of the plate was the same as the P-wave speed in a large solid. Later and more rigorous studies (Sansalone et al., 1987-91), however, have shown that the apparent wave speed relating the thickness frequency and plate thickness is almost 96 % of the P-wave speed, that is, $C_{pp} = 0.96C_p$. This difference occurs because multiple reflections of P-waves excite a specific mode of vibration in the plate the thickness mode and the displacements caused by this mode produce the basic periodic shapes in the waveform (Sansalone & Streett, 1997).

Laboratory experiments and finite-element based computer simulations of stress wave propagation in concrete structures, covering a wide variety of geometric shapes, have shown that for each shape the frequency of the fundamental or first mode of vibration excited by impact is related to the wave speed $C_p$ and a specific dimension $A$ through the equation:

$$f = \frac{\beta C_p}{2A}$$

(2.29)

Where $\beta$ is a shape factor determined by the geometry. In the case of solid plate, the specific dimension is the thickness, $T$ and the shape factor, $\beta$ is:

$$T = \frac{0.96\ C_p}{2f}$$

(2.30)

---

**Fig.2-9: Principle of frequency analysis:**

The time domain waveform has a periodic pattern due to P-wave arrival as it undergoes multiple reflections between the top and bottom of the plate; the frequency of P-wave arrival is related directly to the plate thickness. (Sansalone & Streett, 1997)
Amplitude spectrum
In frequency analysis of impact-echo outcomes, the objective is to determine the dominant frequencies in the recorded waveform. This is completed by using the fast Fourier transform technique to convert the recorded waveform into the frequency domain (Sansalone & Streett, 1997). The results are in an amplitude range that shows the amplitudes of the different frequencies contained in the waveform. For plate structures, the thickness frequency will usually be the dominant peak in the spectrum. The value of the peak frequency in the amplitude spectrum can be used to define the depth of the reflecting interface as follows:

$$T = \frac{c_{np}}{2f}$$  \hspace{1cm} (2.31)

Instrumentation
Impact-echo testing has three basic mechanisms:
- An impacting object capable of producing impacts
- A receiver to measure the surface reply
- A data analysis system to process the waveforms

Fig. 2-10 shows a typical impact-echo test system.

Fig.2-10: Typical impact-echo test system (Carino & Sansalone, 1992)
1) Impacting object 2) Receiver 3) Data analysis system

2.2 Plastic impact waves: Explosive welding

2.2.1 Propagation of plastic waves

Elastic–plastic waves in a long uniform bar
Consider a uniform long bar with linear stress engineering strain curve (see Fig.2-11), such that the two gradients of the curve are E and P where E is the elastic Young’s modulus, P the plastic modulus and Y is the yield stress. If the speed at which the free end of the bar is moved at an instant results in tensile stress $\sigma > Y$, this stress may be transmitted by two waves that move at the different speeds $c_{0e} \sqrt{E/\rho_0}$ and $c_p = \sqrt{P/\rho_0}$. In a nonlinear stress engineering curve for an element with $\varepsilon = \frac{d\sigma}{dx}$ equation (2.9) is illustrated as follows:

$$\frac{\partial^2 u}{\partial t^2} = \frac{d\sigma/dx}{\rho_0}, \frac{\partial^2 u}{\partial x^2}$$  \hspace{1cm} (2.32)
And with solving the wave equation the wave propagation speed is:

$$\sqrt{\frac{\partial^2 \rho_0}{\partial \sigma}}$$

And so, in a linear plastic stress-strain equation the wave speed is:

$$\sqrt{\frac{\sigma}{\rho_0}}$$

Fig. 2-11: a) A uniform long bar with linear stress engineering strain curve
b) Impact of a bar with a rigid anvil (Johanson, 1970)

Impact of a uniform bar with a rigid flat anvil
In this experiment a uniform bar impinges normally on a rigid flat anvil and the normal stress rises to \(\sigma_0 > Y\), where \(Y\) is the yield stress. It is possible to consider only two wave speeds: the elastic wave \(c_0 = \sqrt{E/\rho_0}\) and the plastic wave speed \(c_p = c_1 = \sqrt{\sigma_0/\rho_0}\). There are three regions in the bar, region 1 which is traversed by both the elastic and plastic waves, region 2 which is traversed by only elastic waves and region 3 which is undisturbed (see Fig.2-11b). Using the strain equation, the following equation can be obtained (Johanson, 1970):

$$\frac{c_0}{c_1} = 4.24$$

2.2.2 Explosive welding

The theory of explosive welding, the method of performing the experiments, the material selection and the boundary conditions are described in the licentiate booklet (Tabatabae Ghomi, 2009) and are briefly re-stated in the following paragraphs.

Mechanism and setup
Explosive welding (EXW) is an application of impact mechanics in which an oblique impact occurs at high velocity. The explosive energy is used to form a cold pressure weld. The basic setup for welding two plates is shown in Fig.2-12a. The flyer plate is mounted at a small angle to the base plate which is held on an anvil which can be either a metal plate or a sand bed. The top surface of the flyer plate is covered with a layer or buffer, which may be rubber or a thick coat of plastic. A layer of explosive material in the form of a sheet or powder is laid on top of the buffer and it detonates from the lower edge. A specific distance - the stand-off distance - and an initial angle \(\alpha\) between the flyer and base
plates are necessary for the flyer plate to obtain the required acceleration (Fig. 2-12b). The impact angle (also called the collision or dynamic angle) $\beta$ can vary depending on the plate arrangement.

The EXW process can be divided into three basic phases:

1. Detonation of the explosive charge
2. Acceleration and deformation of the flyer plate
3. Collision of the plates

It is accepted that jet formation at the contact point is an essential condition for the welding. This jet sweeps away the oxide films on the surfaces of the metals and forms a metallurgical bond that causes the atoms of the two materials to meet at atomic scale distances. The pressure has to be sufficiently high and last for a sufficient time for these inter-atomic bonds to be formed. The velocity of the collision point $V_c$ sets the time available for bonding. The pressure also causes local plastic deformation of the metals at the interface. The strength of the bond is stronger than the strength of the weaker plate material, and the quality of the bond depends on careful control of parameters such as surface grounding, plate separation and the detonation velocity $V_d$ (Fig. 2-12b). The impact velocity $V_p$ and the dynamic angle $\beta$ determine the pressure and the shear stress at the collision point.

The impact wave in explosive welding

In EXW the pressure created in the region of the detonation front of the explosive charge is used to provide rapid acceleration of the flyer plate to a high velocity prior to impact on the base plate. The flyer plate velocity depends on the amount of explosive charge and the stand-off distance. The pressure produced in the detonation front transmits into the flyer plate as a stress compression wave. When the compression wave reaches the back surface of the metal slab, it is reflected as a tension wave, and the velocity of particles is doubled (Kolsky, 1963), (Fig. 2-12c). The same phenomenon occurs at the edges of the plates where the impact wave propagates horizontally. This edge effect creates problems for the quality of welding at the edges. The pressure waves in the flyer plate are oblique and when they are reflected from the back surface of the plate, they give rise to both a dilatational wave and a shear wave.

El-Sobky & Blazynski (1975) suggested a mechanism for the stress wave, represented in Fig. 2-12d. In their model, a single compression wave (symbolized by a full circle) is generated at the collision point, while successive reflections from both the flyer and base plate (represented by the dashed circles) generate the wavy shape at the contact point that can be seen under the SEM.

There is production of a rippled or wavy interface. They bring to mind hydrodynamic phenomena and underline the fluid jet treatment previously referred to: they suggest that the pressures at impact are such that materials behave as if they were fluids, i.e. that the pressures are vastly greater than the yield strength of either material. At the high pressures and temperatures prevailing in the collision zone the shear strength becomes negligible compared to the pressure and the metals will behave like fluids. It is therefore proposed to analyse the system hydro-dynamically assuming the metal to flow as a non-viscous fluid; this is not to say that the metal is in a fluid state when moving and deforming.

Kelvin-Helmholtz instability (Wikipedia, 2011) can occur when shear velocity is present within a continuous fluid, or when there is sufficient velocity difference across the interface between two fluid surfaces of different density (Fig. 2-12e). The instability will manifest itself in the form of waves being generated on the water surface. The theory can be used to predict the onset of instability and transition to turbulent flow in fluids of different densities moving at various speeds. Helmholtz studied the dynamics of two fluids of different densities when a small disturbance such as a wave is introduced at the boundary connecting the fluids.

When two fluid streams collide at an appropriate angle and divide into two, a hydrodynamic shear or Helmholtz type of instability is realised in the region of the stagnation point of the boundary where the bifurcation occurs. It will be observed that the internal surface of the metal which passes through the stagnation point is a dividing plane from which part goes to the left and part to the right: this
ensures that clean surfaces are brought together under very high pressure and thus that there should be excellent bonding: the material which forms the jet is ejected as spray so that a kind of surface cleaning precedes welding. Waves or ripples also give rise to good interlocking of the surfaces of the plates.

![Diagram of explosive welding setup](image1)

![Diagram of explosive bonding process](image2)

![Diagram of stress wave mechanism](image3)

Tensile Bond Strength of explosive welds

The Tensile Bond Strength (TBS) of explosive welded joints is a very important parameter in the EXW process. An inter-metallic alloy forms in the collision zone (see Fig.2-13a). The ultimate limit of strength is equal to the yield point of the weaker metal and even less because of residual stresses. The results must be uniform in the entire welding area as shown in Fig.2-13b. It can be checked by tension experiments. The best TBS of explosive welding is: $\sigma = \frac{UTS}{Cte/L}$, where UTS is the ultimate tensile stress of the weaker metal and $Cte/L$ means that it is constant throughout the length of the plates. Fig.2-13c shows the test method used to obtain this diagram. The reflected waves reduce the Tensile Bond Strength (TBS) in the edges, and it is considered to be a major problem. Shock waves reflected at the end of the plates produce spalls and scabs. These can be reduced by using a suitable velocity of explosive charge and suitable regulation of welding, but experiments show a reduction in the strength of bonding in the edges, and formation of bonding in the middle of welded metals (see Fig.2-13d).
Governing equations

In (Tabatabaei Ghomi, 2009) a complete review of the theory and equations of the explosive welding was mentioned. We provide an excerpt from that review in the following paragraphs.

The main governing equation for the EXW process is the equation of motion (ASM, 1983):
\[ \rho V = \nabla \sigma \]
(2.36)

From plasticity theory, the maximum pressure is expressed as:
\[ P = \rho \beta CV_c \]
(2.37)

Using the hydrodynamic method, the maximum pressure is:
\[ P = \rho \frac{V_c^2}{2} \]
(2.38)

In a parallel set up, the following equations are used to calculate the pertaining equations:
\[ V_c = V_f = V_d = V_w = \frac{V_p}{2 \sin(\beta/2)} \]
(2.39)

Wavelength

The wavelength can therefore be determined from the following equation:
\[ \lambda = 28b \sin^2(\beta/2) \]  \hspace{1cm} (2.40)

In addition, we know from experimental data that is obtained as follows (El-Sobky & Blazynski, 1983):

\[ A = 0.2 \lambda \]  \hspace{1cm} (2.41)

**Welding window**

The welding window (WW) includes straight and curved regions. In order to draw the WW the relationships between the initial conditions (the angles \( \alpha \) and \( \beta \) and the characteristics of the explosive) must be established. The WW lies within the boundaries of 7 parameters as shown in Fig.2-14. The parameters \( \alpha, \beta, V_d, V_p, V_f, V_c \) and the properties of the material determine the WW. This diagram can be drawn in both the \( V_c - \beta \) and \( V_p - \beta \) plane and displays an area within which the weld is available. In this thesis the WW is drawn only in the \( V_c - \beta \) plane.

![Welding window diagram](image)

**Fig.2-14: An example of a WW diagram in the Vc-\( \beta \) plane (Crossland, 1982)**

**Critical angle limit for jet formation [line a-a]**

The most important condition for explosive welding is jet formation. This must occur at the contact point for successful welding to occur. Theoretically, jetting will occur if \( V_c \) remains subsonic. However, in practice a minimum angle is necessary to satisfy the pressure requirements. Jetting occurs to the left of the line a-a in Fig.2-14, which represents the critical angle \( \beta_c \) which is necessary for jetting. Abrahamson (1961) suggests the following relationship between \( \beta \) and \( V_c \):

\[ \beta = 10(V_c - 5.5) \]  \hspace{1cm} (2.42)

**Upper limit of \( V_c \) [line b-b]**

Line b-b in Fig.2-14 describes the upper limit of \( V_c \) which is predictable at 1.2 to 1.5 times the speed of sound, and which also limits the other WW parameters.

**Lower and upper limit of \( \beta \) [lines c-c and d-d]**

The lower and upper limits of the dynamic angle \( \beta \) were experimentally obtained by Bahrani and Crossland (1964). They suggested a lower limit of between 2° and 3° and upper limit of 31° for \( \beta \) in a parallel geometry. Suggested minimum and maximum values of the initial angle \( \alpha \) in an inclined set up are 3° and 18° respectively.
Lower limit of $V_c$ [line e-e]
Equation (2.43) defines the lower limit of $V_c$ for bonding as proposed by Simonov (1991).

$$V_c = K (2Hv / \rho)^{1/2}$$

Cowan (1971) defined the lower limit of $V_c$ according to the fluid hypothesis at Reynolds’ number (Re) as follows:

$$Re = \frac{(\rho_F + \rho_B)V_e^2}{2(H_F + H_B)}$$

H is the Vickers hardness [Pa] and F and B stand for flyer and base plates respectively. The lower limit of $V_c$ can be determined at the transition limit which occurs at Re=10.6.

Lower limit of impact critical pressure ($V_p$) [line f-f]
Equation (2.45) shows the lower limit for welding of $\beta$ in radians, where H is the Vickers hardness [Pa] and $\rho$ is the density in kg/m$^3$.

$$\beta = 1.14 \left( \frac{Hv}{ \rho V_e^2} \right)^{1/2}$$

The equation simplifies to:

$$\beta V_c = \text{cte}$$

Hardness is derived from tensile stress as follows (Blazynski, 1983):

$$Hv = 5 \sigma$$

Wittman also proposed a lower limit for $V_p$ as follows (Tabatabaei Ghomi, 2009):

$$V_p = \left( \frac{\sigma TU}{C} \right)^{1/2}$$

Where $\sigma_{TU}$ is the ultimate tensile stress and $C$ is the bulk sound velocity. Equation (2.49) gives another formulation for the lower limit of $V_p$ (El.Sobky, 1983):

$$V_p (\text{Min}) \approx 10 \sigma A \left[ \frac{1 + U_A / \rho B U_B}{\rho A U A} \right]$$

Where A is a symbol for the plate with higher strength, $\sigma$ is yield stress and U is the speed of sound in the metal. Equation (2.50) gives $V_p$ for the plates with the same material:

$$V_p (\text{Min}) \approx \frac{10\sigma}{\rho U}$$

Upper limit of $V_p$ [line g-g]
Wittman gives the upper limit for welding as (Tabatabaei Ghomi, 2009):

$$\sin (\beta/2) = 1 V_c^{1.25}$$
3 Modelling and simulation

As most results of impact process have been obtained by experiments, repetition of similar experiments can be avoided by using modelling and simulation. In addition, result prediction, parameter selection and wave distribution determination can be performed by simulation software. The most important simulation software packages in impact mechanics are ABAQUS, ANSYS, ANSYS-LS-DYNA, ANSYS-AUTODYN and RAVEN. Stress, strain, pressure, temperature distribution, behaviour of materials and displacement of energy can be simulated in two or three dimensions.

3.1 Modelling and simulation of impact-echo

In this thesis ANSYS-LS-DYNA software has been employed to check results of an impact measurement in the elastic deformation zone. LS-DYNA is a general purpose, explicit finite element program used to analyse the nonlinear dynamic response of three-dimensional structures. LS-DYNA's comprehensive selection of material models, element formulations, and contact algorithms have enabled users worldwide to successfully solve many complex automotive safety, failure analysis problems, metal forming and structural. LS-DYNA integrates a number of advanced features including contact handling and error-checking, thermal modelling, adaptive meshing, coupled structure, fluid modelling, bi-material elements, integrated 2D and 3D modelling, and airbag models. LS-DYNA is directly supported by a wide range of 3rd party pre- and post-processing systems. Numerical simulations of the experiments described in the thesis were carried out using LS-DYNA/Explicit version 971 (LS-DYNA, 2007). All plates and projectiles were simulated as axisymmetric.

3.1.1 Identification and modelling setup

In the usual impact-echo method for measuring the thickness of a concrete plate, there must be direct access to one of the surfaces of the plate under test. In buried plates where there is no access to any of the surfaces, this method cannot be applied. In this study we proposed an indirect measurement method that uses a steel bar to transmit the impact signal to the concrete plate. Thus, using this method we can test a concrete plate without the need to access to a big part of the surface of the plate. Fig. 3-1 shows the direct and indirect set-up. In direct method (No.1) a small steel ball is dropped at the top of a large concrete plate (7 meter diameter). A piezoelectric sensor is located on the concrete plate at a distance from the plate centre. An analyser calculates the results of the displacements reported by the sensor. In the indirect method (No.2) a steel rod is located between the steel ball and concrete plate and the sensor is located on the plate. Table 3-1 shows the specifications for the direct and indirect setup.
1 Direct set-up

2 Indirect set-up

Fig. 3-1: Direct and indirect set-up for measuring concrete plates

Table 3-1: Specifications for the direct and indirect setup for impact measurement

<table>
<thead>
<tr>
<th>Setup</th>
<th>Impacting object</th>
<th>Plate</th>
<th>Connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct (concrete)</td>
<td>Steel ball</td>
<td>Concrete</td>
<td>7m diameter</td>
</tr>
<tr>
<td></td>
<td>Φ 10 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indirect (concrete)</td>
<td>Steel ball</td>
<td>Concrete</td>
<td>steel rod</td>
</tr>
<tr>
<td></td>
<td>Φ 10 mm</td>
<td></td>
<td>Φ40mm,L1m</td>
</tr>
<tr>
<td>Direct (Steel)</td>
<td>Steel ball</td>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Φ 10 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.1.2 Modelling procedure

Direct Method
For the numerical investigation, the explicit finite element program LS-DYNA was used. All of the plates and projectiles are simulated as axisymmetric, 2D isotropic models. In the model as shown in Fig. 3-2 the impacting object was described as a spherical projectile with specific initial velocity. The characteristics of the stress waves generated by elastic impact of a sphere on a solid determine their ability to propagate through a material and their usefulness in measuring the thickness amplitude so the initial velocities for various plate thicknesses were as Table 3-2.

<table>
<thead>
<tr>
<th>Initial velocity [m/s]</th>
<th>plate thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>75,100,125</td>
</tr>
<tr>
<td>14</td>
<td>150,200</td>
</tr>
<tr>
<td>20</td>
<td>250,300</td>
</tr>
<tr>
<td>25</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 3-3: Input date for physical specification of the model

<table>
<thead>
<tr>
<th>Part</th>
<th>Young’s modulus E [Gpa]</th>
<th>Poisson ratio ν</th>
<th>Density ρ [kg/m^3]</th>
<th>P-wave speed C_p [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel projectile</td>
<td>210</td>
<td>.3</td>
<td>7850</td>
<td>6020</td>
</tr>
<tr>
<td>concrete plates</td>
<td>33</td>
<td>.2</td>
<td>2300</td>
<td>4000</td>
</tr>
</tbody>
</table>

The physical specification of the model is shown in Table 3-3. In order to compare the results with the previous study (Chia-Chi.et al. 2007), the Poisson ratio and density of all concrete plates are considered equal to this reference is shown in Table 3-3, respectively. The Young’s modulus by using P-wave speed C_p = 4000 m/s for concrete, 6000 m/s for steel and are given by the following equation (Sansalone& Streett, 1997)

$$E = \left( \frac{(1+\nu)(1-2\nu)\rho}{(1-\nu)} \right) C_p^2$$  \hspace{1cm} (3.1)

Indirect Method
As mentioned before in the prevalent impact-echo test for thickness measurement we have direct access at least to one surface of the plate. But in some cases that concrete plate is buried under soil or other materials so that we have no appropriate access to any of the surfaces. Therefore, in this case we introduce a new approach i.e. to drill the cover on the plate and pass a steel bar through it, and then we trigger a steel bar by a projectile from a gun to transfer a stress wave to the plate. Near the bar location we also drilled another hole to pass the Piezoelectric sensor to receive the reflected signals from the bottom of the plate and convey it to a data acquisition system and the corresponding computer. In order to achieve this at this stage a steel projectile was modelled as an impacting object and a steel bar as a transmitter that was attached to the concrete plate surface. All plates, bars and projectiles were simulated as axisymmetric, 2D isotropic models. In the model as shown in the Fig.3-3 the Impacting object was considered to be a spherical projectile with a specific initial velocity. The initial velocity for various plates thicknesses were as Table 3-4.
Table 3-4: Initial velocities for various plate thicknesses

<table>
<thead>
<tr>
<th>Initial velocity [m/s]</th>
<th>plate thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>75, 100, 125, 150</td>
</tr>
<tr>
<td>40</td>
<td>200, 250, 300</td>
</tr>
<tr>
<td>50</td>
<td>400</td>
</tr>
</tbody>
</table>

The bar has the same mechanical properties as the projectile and is 1000 x 200 mm. The length of the 2D-model is 3.5 m, and the mesh size is 2.5 mm for the thicknesses of 75, 100, 125, 150 and 200 mm. In order to compare the results of these two approaches the material properties of the concrete plate was considered similar to those of the direct method mentioned before. The length of the 2D-model was 3.5 m and the mesh size for all of the thicknesses of 75, 100, 125, 150 and 200 mm was chosen to be 2.5 mm.

For the thicknesses of 250, 300 and 400 mm the element sizes from the beginning of the plate to the indicated, and lengths were 2.5 mm and these sizes were 5 mm to the end of the plate. The time interval of the displacement data acquisition was 2.668 µs, and the end time of the each simulation was 2048 times the interval time. When the number of data nears 2048, the displacements near zero. Thus, to increase the resolutions of F.F.T analysis, sufficient zeroes at the end of the data record size were added. This approach resulted in four times the time domain (8192).

Fig. 3-2: Modelling of the direct method in LS-DYNA

Fig. 3-3: Modelling of the indirect method in LS-DYNA

As stated above, the impact echo method is used normally for measuring the thickness of concrete plates. In the next part the possibility of using impact waves for measuring the thickness of steel plates is investigated. The model is chosen as follows:
Steel plate
For the numerical investigation, the explicit finite element program LS-DYNA was used. All of the plates and projectiles were simulated as axisymmetric, 2D isotropic models. In the model as shown in the Fig.3-2 the impacting object was described as a spherical projectile with specific initial velocity. The characteristics of the stress waves generated by elastic impact of a sphere on a solid determine their ability to propagate through a material and their usefulness in measuring the thickness amplitude. So the initial velocities for various plate thicknesses were as the Table 3-5.

<table>
<thead>
<tr>
<th>Initial velocity [m/s]</th>
<th>plate thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>30, 40</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>30</td>
<td>75, 100</td>
</tr>
</tbody>
</table>

The mechanical properties for both steel projectile and steel plate are the same as the model for the direct method was shown in Table 3-2. The P-wave speed $C_p$ is given by equation (3.1).

The length of the 2D-model is 3.5m and the mesh size for all models was chosen to be 2.5 mm. The time interval of the displacement data acquisition was 1.334 μs that is considered the sensor frequency of the previous work (Chia-Chi.et al. 2007) and the end time of the each simulation was 4096 times the interval time, in order to supply sufficient data for FFT analysis.

3.2 Modelling and simulation of explosive welding

Numerical simulations of the experiments described in this thesis were carried out using ABAQUS/Explicit version 6.9-1 (ABAQUS, 2009). The ABAQUS software was used to validate results in explosive welding plastic deformation.

AB AQUS
Abaqus is an engineering simulation software package, based on the finite element method that can solve problems including simple linear analyses and difficult nonlinear simulations. Abaqus covers wide library of elements that can model almost any geometry. It has a similarly wide list of material simulations that can simulate the activities of most materials including concrete, composites, metals, foams, polymers, rubber, soils and rock. Abaqus can be used to study stress/displacement problems. It can simulate problems in such various areas as heat transfer, acoustics, impact/crash, soil mechanics, and piezoelectric analysis. In a nonlinear analysis Abaqus automatically indicates suitable load increments and convergence tolerances and modifies them during the analysis to confirm that an exact solution is found efficiently (ABAQUS, 2009).

Abaqus/Standard
Abaqus/Standard is a general-purpose analysis product that can solve a wide range of linear and nonlinear problems including the static, dynamic, thermal, and electrical reply of mechanisms. Abaqus/Standard solves a system of equations simplifying at each solution increment (ABAQUS, 2009).

Abaqus/Explicit
This software is a special purpose product that uses explicitly finite element method for solving dynamic problems. It is suitable for modelling transitory dynamic events, such as blast and impact simulations, and is also very efficient for extremely nonlinear problems including changing contact situations, such as forming and welding problems. Abaqus/Explicit operates in small time increments without solving a coupled system of equations at each increment.
3.2.1 Identification and modelling setup

According to the experimental set up, a new method in explosive welding of unequal surfaces was presented. In this way making grooves on the flyer plate was suggested. This model was simulated approximately in actual size with simple and grooved set up are according to the specifications in Table 3-6 and Fig. 3-4. The specifications for the models are shown in Fig.3-4. In this figure plate No.1, specifies an aluminium sheet which is coloured as grey and is placed on the copper plate. A new improved method is shown in No.2 in which a 5 mm thickness plate (with different depths depth of groove) is modelled. Fig 3-4 No.3 shows the method of placing the explosive material on the aluminium plate and the stand-off distance.

<table>
<thead>
<tr>
<th>Model</th>
<th>Flyer plate [mm]</th>
<th>Base plate [mm]</th>
<th>Stand-off [mm]</th>
<th>Groove depth [mm]</th>
<th>Distance of grooves from the edges [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td>Al 50× 150 × 5</td>
<td>Cu-150 × 250 × 15</td>
<td>8</td>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>Grooved</td>
<td>Al 50× 180 × 5</td>
<td>Cu-150 × 250 × 15</td>
<td>8</td>
<td>1,2,3,4</td>
<td>10</td>
</tr>
</tbody>
</table>

3.2.2 Modelling procedure

Starting with a known initial geometry, a suitable model for numerical simulation can be designed. A three-dimensional case using C3D8R (ABAQUS, 2009) elements are used in Abaqus/Explicit. The model is constructed of three parts: part 1=base plate of copper material, part 2=flyer plate of aluminium material and part 3=explosive material. They have 61776, 40765, and 340 mesh respectively according to Table 3-7. In the areas close to the collision zones, a mesh size of about 1mm was used, whereas in other areas the mesh was made larger (about 5 times). Therefore in part 1 at the contact point the mesh was refined (1/5).

The regular progress of steady state collision geometry and the deformation prototype were calculated from the basic equations of motion. The constitutive materials of the flyer and base plates were aluminium and copper respectively. The Johnson-Cook plastic strain hardening and failure criteria parameters used in this study were presented in material modelling section. The flyer and base plates were modelled using Arbitrary Eulerian-Lagrangian formulation for both components (ABAQUS, 2009). The JWL EOS was used for the explosive. In the ABAQUS code, energy and momentum transfer occurred through contact surfaces between the base of the explosive and the upper surface of the flyer plate and between the lower surface of the flyer plate and the upper surface of the base plate. The lower surface of the base plate was fixed in a direction perpendicular to its surface. The interactions were specified by appropriate contact algorithms. The loading is due to the detonation of the PETN high explosive with various thicknesses.

Bulk viscosity introduces damping associated with volumetric straining. Its purpose is to improve the modeling of high-speed dynamic events. Abaqus/Explicit contains two forms of bulk viscosity: linear and quadratic. Linear bulk viscosity is included by default in an Abaqus/Explicit analysis. Linear bulk viscosity parameter and Quadratic bulk viscosity parameters were chosen .06 and 1.2 respectively. Friction was also included in the modelling with a value of about 0.3 chosen as optimum for the coefficient of friction. Comprehensive descriptions of the modelling can be found in (ABAQUS, 2009).
The model for tests with improved groove setup is shown in Fig.3-5. The explosive thickness was divided into 60 elements. The flyer plate is modelled using 90 thickness elements. The base plate was divided into 200 elements through its thickness with appropriate grading. In all cases, fine mesh size was used in regions near the contact surfaces, further away the mesh was made coarser.

Fig. 3-4: Modelling of unequal surface Al-Cu EXW joint in ABAQUS
No. 1) The simplified model in which the aluminium sheet is placed on the copper plate.
No. 2) A new improved method in which a 5 mm thickness plate with different depth of groove is modelled.
No. 3) The method of placing the explosive material on the aluminium plate and the stand-off distance.
Table 3-7: Specification of mesh in the models

<table>
<thead>
<tr>
<th>Name</th>
<th>No. elements</th>
<th>No. nodes</th>
<th>Element type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simple</td>
<td>Grooved</td>
<td>Simple</td>
</tr>
<tr>
<td>Base plate</td>
<td>61776</td>
<td>61776</td>
<td>70310</td>
</tr>
<tr>
<td>Flyer plate</td>
<td>30000</td>
<td>40756</td>
<td>38505</td>
</tr>
<tr>
<td>Explosive</td>
<td>300</td>
<td>340</td>
<td>682</td>
</tr>
</tbody>
</table>

Fig.3-5: Modelling of groove method in ABAQUS
3.2.3 Material modelling

The material model is an important factor affecting the accuracy of results of a finite element simulation. The Johnson-Cook constitutive model duplicates several important material responses observed in impact of metals. The three key material responses are strain-rate effects, strain hardening, and thermal softening. These properties are combined in the Johnson-Cook constitutive model (ABAQUS, 2009).

\[
\bar{\sigma} = \left[ A + B (\dot{\varepsilon}^{pl})^n \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}^{pl}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T-T_0}{T_{melt}-T_0} \right)^m \right] \tag{3.2}
\]

Where \( \dot{\varepsilon}^{pl} \) is equivalent plastic strain rate, \( \bar{\sigma} \) is equivalent stress, \( \dot{\varepsilon}_0 \) is a reference strain rate, \( A, B, C, n, \) and \( m \) are material parameters.

The fracture model suggested by Johnson and Cook takes into account the result of stress, temperature and strain rate. Failure is assumed to occur when the damage parameter \( D \) exceeds unity. The damage parameter, \( D \), is defined as follows:

\[
D = \sum \left( \frac{\Delta \varepsilon^{pl}}{\varepsilon_f} \right) \tag{3.3}
\]

Where \( \varepsilon_f \) is the equivalent strain at failure, \( \Delta \varepsilon^{pl} \) is the increment of the equivalent plastic strain, and the summation is performed over all increments of deformation. \( \dot{\varepsilon}^{pl}/\dot{\varepsilon}_0 \) is a dimension-less pressure–deviatory stress ratio. The strain at failure \( \varepsilon_f^{pl} \) is assumed to be dependent on a non-dimensional plastic strain rate, \( \sigma_m/\bar{\sigma} \) (where \( \sigma_m \) is the mean stress). The strain is defined as follows:

\[
\varepsilon_f^{pl} = \left[ D_1 + D_2 \exp \left( D_3 \frac{\sigma_m}{\bar{\sigma}} \right) \right] \left[ 1 + D_4 \ln \left( \frac{\dot{\varepsilon}^{pl}}{\dot{\varepsilon}_0} \right) \right] + \left( 1 + D_5 \left( \frac{T-T_0}{T_{melt}-T_0} \right) \right) \tag{3.4}
\]

Where \( D_1-D_5 \) are material constants.

For the explosive, the Jones–Wilkins–Lee equation of state was selected to indicate the expansion of the explosive materials. The JWL equation of state defines pressure as function of internal energy per initial volume, \( E \); and specific volume (inverse of density), \( V \); as (ABAQUS, 2009):

\[
P = A(1 - \frac{\omega}{R_1V}) e^{-R_1V} + B(1 - \frac{\omega}{R_1V}) e^{-R_2V} + \frac{\omega E}{V} \tag{3.5}
\]

Where \( P \) is the pressure, \( E \) is the internal energy, \( V \) is the specific volume, \( \omega \) is the Gruneisen parameter, and \( A; B; R_1 \) and \( R_2 \) are constants which satisfy the mass, momentum, and energy saving equations.

The material parameters for the model in this study are presented in the Table 3-8.
Table 3-8: Input material parameters for the models in ABAQUS

<table>
<thead>
<tr>
<th>Material behaviour</th>
<th>Material parts</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
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<td>Aluminium</td>
<td>Copper</td>
<td>explosive</td>
<td>sand</td>
</tr>
<tr>
<td>1</td>
<td>Johnson-Cook damage</td>
<td>D1</td>
<td>.112</td>
<td>-0.191</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D2</td>
<td>.123</td>
<td>5.91</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>D3</td>
<td>1.5</td>
<td>4.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D4</td>
<td>.007</td>
<td>-0.052</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D5</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
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<td></td>
<td>T melt [k]</td>
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<td>1357</td>
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<td></td>
<td>T transition [k]</td>
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<td>297</td>
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</tr>
<tr>
<td>2</td>
<td>Damage Evolution</td>
<td>Type</td>
<td>Energy</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Softening</td>
<td>Exponential</td>
<td>Exponential</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Degradation</td>
<td>Maximum</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fracture energy</td>
<td>500 [MPa]</td>
<td>500 [MPa]</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Density [kg/cm³]</td>
<td>2700</td>
<td>8940</td>
<td>880</td>
<td>8000</td>
</tr>
<tr>
<td>4</td>
<td>Elastic</td>
<td>Isotropic</td>
<td>Young’s Modulus [GPa]</td>
<td>69</td>
<td>117</td>
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<tr>
<td></td>
<td></td>
<td>Scale: long-term</td>
<td>Poisson Ratio</td>
<td>.3</td>
<td>.3</td>
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<td></td>
<td></td>
<td>For viscoelasticity</td>
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<td></td>
<td></td>
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<tr>
<td>5</td>
<td>Plastic</td>
<td>A [MPa]</td>
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<td>95</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B [MPa]</td>
<td>684</td>
<td>280</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>.73</td>
<td>0.35</td>
<td></td>
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<td></td>
<td></td>
<td>m</td>
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<tr>
<td></td>
<td></td>
<td>ε₀</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>.011</td>
<td>.02</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Explosive Model</td>
<td>Detonation velocity [m/s]</td>
<td>5170</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>A [GPa]</td>
<td>348</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B [GPa]</td>
<td>11.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ω</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>R1</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>R2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pre-detonation Bulk modulus</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4 Experiments

4.1 Impact-echo experiments

The experiment has been done in Construction Materials Institute (CMI) by a portable impact echo system (PIES). In this experiment was intended to compare the two direct and indirect methods.

Problem definition

In the usual impact-echo method for measuring the thickness of a concrete plate, there must be direct access to one of the surfaces of the plate under test. In buried plates where there is no access to any of the surfaces, this method cannot be applied. In this study we proposed an indirect measurement method that uses a steel bar to transmit the impact signal to the concrete plate. Thus, using this method we can test a concrete plate without the need to access to a big part of the surface of the plate.

Experimental setup

Fig. 4-1 and Table 4-1 show arrangements for the two methods of concrete thickness measurement: the direct method setup and the indirect method setup. In direct method a small steel ball is knocked at the top of concrete plate. In the indirect method a steel rod is located between the steel ball and concrete plate and the sensor is located on the plate. Samples of concrete according to the simulated method have been built. The material and the granularity of all samples were the same and it is accordant concrete standards. The samples had been placed on free surface. The signal analyzing had been done by the PIES. Thickness measurement, computing concrete specification and crack location detection are features available in the PIES. But the system was sat to be used for thickness measurement and the results were obtained as frequency – amplitude in graph and Excel file.

Fig. 4-1: Setup the experiments
S1) Portable Impact-Echo System, S2) Concrete plate, S3) Direct method set up, S4) Indirect method set up
### 4.2 Explosive welding experiments

The experiments for solving the edge problem in unequal surface Al–Cu EXW joints were performed in a vacuum chamber.

#### Problem definition
Unequal surface Al–Cu EXW joints are used to transmit the electric power of anode rods in the aluminium factory (see Fig.4-2). The edge problem reduces electrical effectiveness of the joints, so a new method was used to increase the quality of TBS.

**Fig.4-2: An Unequal surface Al–Cu EXW joint**

#### Old methods for removing edge problem
According to the previous section the impact wave’s reflection creates problems for the quality of welding at the edges and produces scabbing and spalls at the edges of plates. Scab and spall problems can be solved by cutting the edges or making the plates larger. Both these methods are uneconomical and are used when both plates are of the same size and shape. Another method is to make the flyer plate bigger than the base plate and then cut the joint after welding. However, these methods cannot solve the problem when the flyer plate is smaller than base plate.

#### Background
McKee and Crossland (1982) mentioned observed abnormal behaviour in their experiments when a step was created in the base plate surface (see Fig.4-3). At low velocity the interface waves initiated...
before the step were maintained by the step, and in other cases the waves before the step were completely damped out by the step and there was no indication of reinitiating. At high velocity the step was shown to have a negligible effect on the waves.

![Fig.4-3: Step in base plate to initiate waves (El-Sobky,1983)](image)

**New groove method**
Based on several experiments we suggested a new method to remove the edge effect. The cutting of thin grooves near the edges of the flyer plate appears to solve the problem (see Fig.4-4). In the new method there is no need to cut and size the plates to improve the Tensile Bond Strength, because the loading of impact waves cuts off the edges beyond the groove, and thereby makes a uniform weld.

![Fig.4-4: Position of grooves in flyer plate to reduce edge problems](image)

**Location of grooves**
The dimensions and coordinates of the grooves were determined experimentally and based on the previous works. Then the optimum values were calculated. For example the distance of groove from the edges assumed to be a little more than 1.5 times the thickness of the flyer plate (about 10mm). The depth of groove was considered to be the maximum depth available for machining, in other words about 4 mm of the 5 mm thickness of the flyer plate. The thickness of groove was chosen as 1mm for ease of machining.

**Experimental setup**
The experiments were performed in a vacuum chamber at the explosive welding laboratory at Tarbiat Modares University. Fig. 4-5 shows the experimental. Fig.4-5 and Table 4-2 show arrangements for the two methods of welding of unequal surfaces Al-Cu joints: the simple method setup and the improved groove method setup.

![Experimental setup](image)

**Table 4-2: Specification of Al-Cu, unequal surface method setup**

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Flyer Plate(Al)</th>
<th>Base Plate(Cu)</th>
<th>Explosive(PETN)</th>
<th>Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width [mm]</td>
<td>Length [mm]</td>
<td>Thickness [mm]</td>
<td>Width [mm]</td>
<td>Length [mm]</td>
</tr>
<tr>
<td>Simple Method</td>
<td>50</td>
<td>150</td>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>Groove Method</td>
<td>70</td>
<td>180</td>
<td>5</td>
<td>150</td>
</tr>
</tbody>
</table>
Fig. 4-5: Setup the experiments
S1) Vacuum chamber, S2) Explosion setup for experiments,
S3) Simple setup for Al-Cu unequal surface joint,
S4) Improved setup for Al-Cu unequal surface joint with grooves
5 Results

After modelling and arranging the tests, simulations were performed in the two fields of IE and EXW. Then the tests were performed at the defined settings. After completing the tests, quality control tests were performed to identify the accuracy of the results. Table 5-1 presents an overall view of the types and number of performed experiments and shows the simulations in two elastic and plastic regions in the time period of the experiments. As mentioned in this table, most of the EXW tests belong to the licentiate period and were elaborated in that booklet (Tabatabaee Ghomi, 2009).

Table 5-1: Total result of the work

<table>
<thead>
<tr>
<th>Name of model</th>
<th>Method</th>
<th>Solution</th>
<th>Period</th>
<th>Name of quality tests*</th>
<th>No. of simulation runs</th>
<th>No of simulation Outputs</th>
<th>No. of experiments</th>
<th>No.of quality tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>IE</td>
<td>Direct</td>
<td>concrete plate</td>
<td>PhD</td>
<td></td>
<td>5</td>
<td>25</td>
<td>5</td>
<td>**</td>
</tr>
<tr>
<td>IE</td>
<td>Direct</td>
<td>steel plate</td>
<td>PhD</td>
<td></td>
<td>5</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IE</td>
<td>Indirect</td>
<td>concrete plate</td>
<td>PhD</td>
<td></td>
<td>5</td>
<td>25</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>EXW</td>
<td>Equal surface flat-horizontal</td>
<td>Fe-Fe joint</td>
<td>Lic.</td>
<td>VD Peel off</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>EXW</td>
<td>Equal surface flat-horizontal</td>
<td>Al-Cu joint</td>
<td>Lic.</td>
<td>VD Peel off</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>EXW</td>
<td>Equal surface flat-horizontal</td>
<td>Fe-Al joint</td>
<td>Lic.</td>
<td>VD Peel off</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>EXW</td>
<td>unequal surface flat-horizontal</td>
<td>Al-Cu joint</td>
<td>Lic./PhD</td>
<td>Tensile SEM Peel off VD</td>
<td>6</td>
<td>60</td>
<td>2 Product (1200)</td>
<td>32</td>
</tr>
<tr>
<td>EXW</td>
<td>unequal surface flat-vertical</td>
<td>Al-Cu joint</td>
<td>Lic.</td>
<td>Tensile SEM Peel off</td>
<td>2</td>
<td>32</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>EXW</td>
<td>unequal surface curve-pipes</td>
<td>cu-Fe joint</td>
<td>Lic.</td>
<td>Peel off</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21</td>
<td>135</td>
<td>21+(1200)</td>
<td>102</td>
</tr>
</tbody>
</table>

*All quality tests including VD (detonation velocity), peel off tensile tests and SEM tests are done in licentiate Thesis (Tabatabaee Ghomi, 2009).

**This session is referred to the corresponding results from the work of Chia-Chi. (2007).

In total, the simulation programs were run more than 21 times using two different software and more than 135 useful outputs were obtained that will be summarized later. In the explosive welding part of our experiments more than 21 types of experiments were carried out and more than 100 quality control tests were performed on the obtained results. Regarding the demand of one of these experiments, more than 1000 test assemblies were mass produced.

The studies and development of new approaches presented in this thesis were performed by conducting a comprehensive study on the impact energy methods in the two areas of elastic and...
plastic deformations with applications in dimensional measurement and explosive welding. In the
dimensional measurement application, two methods were used for controlling the output results. In
the first method an actual dimension was assumed and simulation tools and wave behaviour were used
to compute that dimension. In the second method the obtained results were evaluated by comparing
them with the results reported in the new research works conducted in concrete plate non-destructive
testing. There were also used some methods for controlling the results obtained in the explosive
welding tests. At first the tests were made and the results controlled by performing mechanical tests.
Using simulation tools and also the quality control criteria provided by other researchers (Al-Hassani
et al. 1985-2005), the simulation results were evaluated and compared with the results of the tests.
This is because I intended to use the outcomes of this research in industry and thus, must assure
reliability of the results.

5.1 Impact-echo results

Output stages for obtaining results are as below:

1. Running the program for all models with different thicknesses and initial velocities
2. Choosing a displacement contour in y direction for all nodes and elements
3. Choosing an element near the center on the top of the plate surface
4. Plotting displacement-time graph for the element by LS-DYNA
5. Saving the export data of the graph in a file
6. Opening the data file in MATLAB or EXCEL software and drawing an FFT graph with the
   program in amplitude-frequency curve
7. Choosing the peak amplitude data of the curve and saving the frequency data \( f \) as an input
data for the equation
8. Calculating the plate thickness by the equation
9. Comparing the simulation result by an impact echo system
10. Obtaining other outputs from the LS-DYNA including: displacement in all direction, stress,
    wave reflections and other parameters

5.1.1 Thickness measurement results

Concrete plate

Stage 1&2
At first the program was run for direct and indirect models with different thicknesses and initial
velocities and then was chosen displacement of a node at the top of the plate according to the Fig. 5-1.
A piezoelectric transducer is placed at a suitable distance from the location of the impact on top of the
concrete plate. Thus, in the simulations performed, a single node is used at the top surface of the plate
at a specific distance \( r \) from the location of the impact to receive the reflected waves from the
bottom of the plate (Fig. 5-1).

Stage 3&4
An element was chosen near the center and on the top of the plate for all models and then was plotted
displacement versus time plot by LS-DYNA. A typical plot for 75 mm thickness is illustrated in
Fig.5-2.

Stage 5
The export data of the graphs were saved in the files. Export data of a displacement-time file are
illustrated in Table 5-2.
Stage 6
At this stage the export data files were opened in MATLAB and were drawn as amplitude vs. frequency FFT graph. The simulation data from LS-DYNA are in the form of displacement-time curves. It is difficult to capture the necessary information from these curves because the time interval of impact wave propagation between the top and bottom surfaces of the concrete plate is challenging to observe directly. The FFT can be employed to determine a frequency analysis on the time-domain data. The resulting amplitude-frequency curves are more suitable than the displacement-time curves, and the necessary information such as the thickness of the concrete plate or the location of the cracks can be captured more accurately. An example of these analyses is shown in Fig. 5-3. Fig 5-4 and 5-5 also show the process in the stages 4 and 6 for direct and indirect method of 150 mm plate thickness.

Fig. 5-1: Displacement of nodes and elements in direct and indirect methods by LS-DYNA
Fig. 5-2: Displacement- time LS-DYNA result for 75 mm thickness

Table 5-2: A typical displacement- time export data saved in NOTEPAD by LS-DYNA

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000000e+00</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>1.319275e-006</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>2.638549e-006</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>3.999051e-006</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>5.318326e-006</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>6.637601e-006</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>7.998103e-005</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>9.155273e-005</td>
<td>-5.187988e-004</td>
</tr>
<tr>
<td>1.063665e-005</td>
<td>-1.312256e-003</td>
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<tr>
<td>1.199716e-005</td>
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<td>1.331640e-005</td>
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</tr>
<tr>
<td>1.599610e-005</td>
<td>-3.053e-003</td>
</tr>
<tr>
<td>1.731528e-005</td>
<td>-3.053e-003</td>
</tr>
</tbody>
</table>

Fig. 5-3: Transformation from time-domain to frequency-domain (Results for a plate thickness of 75 mm in the indirect method)
Stage 7&8

FFT analysis of the displacement-time waveform can be used to transform a simulated waveform to a frequency domain curve. In a concrete plate structure, the dominant peak in the spectrum determines the thickness frequency that is used to calculate the thickness of the structure as stated in equation (2.30). Fig.5-5 shows that with the numerical response of a 150 mm thick plate, the dominant frequency of 12.72 KHz can be obtained.

The analysis presented in this thesis assumes that the velocity of wave propagation in the concrete is equal to 4000 m/s. Therefore, the value of $\beta$ is calculated from equation (2.29) and found to be equal to 0.954. Thus, the equation can be written as follows:

$$T = \frac{0.954 \, C_p}{2f} \quad (5.2)$$

Table 5-3 summarizes the overall results of the FFT figures. The difference between the measured and the actual thickness is reflected in the last column of the table.

Stage 9

Tables 5-4 and 5-5 show the results of experiments according to the illustrated arrangements in Fig.4-1 and Table 4-1.
Table 5-3: Comparison between the results of the direct and indirect methods

<table>
<thead>
<tr>
<th>Actual Plate Thickness $T$ [mm]</th>
<th>Direct Thickness Frequency $f$ [1/sec]</th>
<th>Indirect Thickness Frequency $f$ [1/sec]</th>
<th>Direct Thickness by Formula $T_d$ [mm]</th>
<th>Indirect Thickness by Formula $T_i$ [mm]</th>
<th>Direct and indirect thickness difference</th>
<th>Difference between Measured and Actual Thickness $(\frac{T_i-T_d}{T})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>25.44</td>
<td>25.44</td>
<td>75.00</td>
<td>75.00</td>
<td>0</td>
<td>0.0000</td>
</tr>
<tr>
<td>100</td>
<td>19.08</td>
<td>19.08</td>
<td>100.03</td>
<td>100.03</td>
<td>0</td>
<td>0.0003</td>
</tr>
<tr>
<td>125</td>
<td>15.28</td>
<td>15.28</td>
<td>124.87</td>
<td>124.87</td>
<td>0</td>
<td>-0.0010</td>
</tr>
<tr>
<td>150</td>
<td>12.72</td>
<td>12.72</td>
<td>150.00</td>
<td>150.00</td>
<td>0</td>
<td>0.0000</td>
</tr>
<tr>
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<td>7.59</td>
<td>251.25</td>
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<td>6.36</td>
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<tr>
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<td>4.80</td>
<td>397.17</td>
<td>397.17</td>
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<td>-0.0070</td>
</tr>
</tbody>
</table>

Table 5-4: Portable impact-echo system results for model No.1 (T=16cm)

<table>
<thead>
<tr>
<th>Test NO.</th>
<th>Point NO.</th>
<th>Peak frequency (HZ)</th>
<th>$T$ (cm)</th>
<th>Excel Data</th>
<th>FFT curve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Amplitude/frequency</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Frequency (HZ)</td>
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<tr>
<td>1</td>
<td>2</td>
<td>6849</td>
<td>15.4</td>
<td>5870</td>
<td>16680</td>
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<td>Direct method</td>
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<td></td>
<td></td>
<td>6360</td>
<td>20121</td>
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<tr>
<td></td>
<td></td>
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<td>6849</td>
<td>35505</td>
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<td></td>
<td>7827</td>
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<td>3</td>
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<td>5381</td>
<td>2397</td>
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<td>5870</td>
<td>18848</td>
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<tr>
<td>3</td>
<td>2</td>
<td>6360</td>
<td>16.6</td>
<td>4403</td>
<td>3139</td>
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<td>Indirect method</td>
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<td></td>
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<td>4892</td>
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<td>3098</td>
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<td>2289</td>
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<td></td>
<td>7338</td>
<td>7972</td>
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<tr>
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<td>3</td>
<td>6360</td>
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<td>15306</td>
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<td></td>
<td>7338</td>
<td>1963</td>
</tr>
</tbody>
</table>
Table 5-5: portable impact-echo system results for model No.2 (T=8cm)

<table>
<thead>
<tr>
<th>Test NO.</th>
<th>Point NO.</th>
<th>Peak frequency (Hz)</th>
<th>T (cm)</th>
<th>Excel Data</th>
<th>FFT curve</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Amplitude (10^-6 V)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Frequency (Hz)</td>
<td></td>
</tr>
<tr>
<td>Direct method 2</td>
<td>1</td>
<td>5871</td>
<td>7.8</td>
<td>6088</td>
<td>4403</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1251</td>
<td>4892</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4604</td>
<td>5381</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>62466</td>
<td>5871</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4691</td>
<td>6360</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3586</td>
<td>6849</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6094</td>
<td>7338</td>
</tr>
<tr>
<td>Indirect method 2</td>
<td>2</td>
<td>5871</td>
<td>7.8</td>
<td>4403</td>
<td>7490</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12900</td>
<td>4892</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18851</td>
<td>5381</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>38852</td>
<td>5871</td>
</tr>
<tr>
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<td>8184</td>
<td>6360</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19224</td>
<td>6849</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9932</td>
<td>7338</td>
</tr>
</tbody>
</table>
| Steel plate | According to stages1-4, as mentioned before, the displacement-time graph was drawn for the steel plate model. Fig.5-6 shows the result for the plate thickness 60 mm. For obtaining the shape factor for steel plate in our analyses we consider the velocity of wave propagation in the steel equal to 6020.18 m/s. Therefore the value of \( \beta \) is calculated from equation (2.30) to be equal to 0.93. So, the equation can be written as follows: \[
T = \frac{0.93 \cdot C_p}{2f} \quad (5.3)
\]
Fig 5-6: Results for the plate thickness 60 mm

The simulation data from LS-DYNA are in the form of displacement-time curves. The FFT can be employed to determine a frequency analysis on the time-domain data. According to stages 4-6 the export data files were opened in MATLAB and were drawn amplitude–frequency by FFT graph. Figs 5-7 to 5-11 show the FFT results for 30, 40, 60, 75, 100 mm plate thickness. The accordance between the thickness frequencies obtained in this study for different thicknesses of steel plate and actual plate thicknesses shows that the impact echo method can be used thoroughly to measure the thickness of steel plates, too. This is obvious by observing Table 5-6 that summarizes the overall results.

Fig. 5-7: Numerical response of a plate with 30 mm thickness

Fig. 5-8: Numerical response of a plate with 40 mm thickness
Fig 5-9: Numerical response of a plate with 60 mm thickness

Fig 5-10: Numerical response of a plate with 75 mm thickness

Fig 5-11: Numerical response of a plate with 100 mm thickness
Table 5-6: Comparison between Measured and Actual Thickness

<table>
<thead>
<tr>
<th>Actual Plate Thickness (T) [mm]</th>
<th>Thickness Frequency f [1/sec]</th>
<th>Thickness by Formula T_s [mm]</th>
<th>Difference between Measured and Actual Thickness (T_s – T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>92.91</td>
<td>30.13</td>
<td>0.004</td>
</tr>
<tr>
<td>40</td>
<td>69.51</td>
<td>40.27</td>
<td>0.007</td>
</tr>
<tr>
<td>60</td>
<td>46.11</td>
<td>60.71</td>
<td>0.012</td>
</tr>
<tr>
<td>75</td>
<td>37.03</td>
<td>75.60</td>
<td>0.008</td>
</tr>
<tr>
<td>100</td>
<td>28.17</td>
<td>99.37</td>
<td>-0.006</td>
</tr>
</tbody>
</table>

5.1.2 Wave propagation results

Stage 10
At this stage was processed other output from the LS-DYNA as below:

Evaluation of plate thickness
The impact response of the concrete plate was simulated by LS-DYNA and is shown in Fig. 5-12. The spherical wave fronts in Fig. 5-12a show how the P-wave and S-wave propagate through the solid.

Wave propagation along the bar and plate and the corresponding reflections
In the indirect method, the steel bar receives an impact from the spherical steel ball. This impact generates compressive stress waves that propagate through the bar as shown in Fig. 5-13, 14, 15.

![Fig. 5-12: Finite element simulation of impact on a plate](image)
Fig. 5-13: Finite element simulation of impact on steel bar and concrete plate (results for the plate thickness 150mm).

Steps 25, 80, 85, 90 and 140
Fig. 5-14: Finite element simulation of impact on steel bar and concrete plate (results for the plate thickness 150mm) - Steps 156, 158, 160, 170, and 210.
Fig. 5-15: Finite element simulation of impact on steel bar and concrete plate (results for the plate thickness 150mm).

Steps 230, 250, 300, and 1900.
5.2 Explosive welding results

Output stages for obtaining results are as below:

1. Performing the experiments for simple and grooved method
2. Performing the mechanical test and SEM test for the experiments
3. Running the programs for simple and grooved models with different depth of grooves
4. Choosing the best depth for grooves according to the simulation results
5. Plotting effective plastic strain, maximum shear stresses, Johnson-cook plastic strain contour for all models by ABAQUS
6. Saving the export data of the graph for interface elements in a file
7. Opening the data file in EXCEL and drawing Effective Plastic Strain and Shear Stress curves
8. Evaluating the results with valid parameters and comparing these with experiments
9. Obtaining the other outputs from ABAQUS including: displacement, strain, stress, pressure and other parameters

5.2.1 Experimental results

Stage 1
In the experiments, using flyer plates with and without grooves, the edges of the grooved plate were cut due to the impact waves generated during the welding. Because of the positions of the grooves, both resulted welds are shown in Fig. 5-16.

![Fig. 5-16 : Result the EXW experiments](image)

R1) Al-Cu unequal surface joint without grooves, R2) Al-Cu unequal surface joint with grooves

Stage 2
Table 5-7 shows the results of tensile bond strength (TBS) in width direction (according to the method as shown in Fig. 2-13), and the illustrated result is illustrated in Fig 5-17. The tests showed that the Tensile Bond Strength was constant in the improved grooves method throughout the contact surface and was low at the edges in simple setup.

<table>
<thead>
<tr>
<th>L [mm]</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>45</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ (simple) [N/mm²]</td>
<td>0</td>
<td>69</td>
<td>177</td>
<td>177</td>
<td>177</td>
<td>177</td>
<td>69</td>
<td>0</td>
</tr>
<tr>
<td>σ (grooved) [N/mm²]</td>
<td>147</td>
<td>177</td>
<td>177</td>
<td>186</td>
<td>177</td>
<td>17</td>
<td>177</td>
<td>137</td>
</tr>
</tbody>
</table>
5.2.2 Simulation results

Stage 3
Fig. 5-18 shows JCCRT- Johnson-Cook plastic strain contour for 4mm depth of groove according to Table 5-8 for different shapes of models.

Stage 4
By iterating the simulation with different depths, the suitable depth for the separation of part 1 from the flyer plate is determined to be 4mm (Fig. 5-19 and Fig. 5-20). In other words, for obtaining the suitable results, up to 1mm of the end of flyer plate must be grooved.
Table 5-8: Model of flyer plate with different depth of grooves
No.1) Flyer plate without grooves (simple method), No.2) Flyer plate with 1 mm depth of grooves, No.3) Flyer plate with 2 mm depth of grooves, No.4) Flyer plate with 3 mm depth of grooves, No.5&6) Flyer plate with 4 mm depth of grooves

<table>
<thead>
<tr>
<th>No.</th>
<th>Shapes of flyer plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>2</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image4" alt="Image" /></td>
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<tr>
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<td><img src="image5" alt="Image" /></td>
</tr>
<tr>
<td>6</td>
<td><img src="image6" alt="Image" /></td>
</tr>
</tbody>
</table>

Fig. 5.19: JCCRT- Johnson-Cook plastic strain contour hardening and failure criteria parameters; Time = (103 μs), Cutting the edges during the explosion at 4 mm depth of groove
Stage 5

For studying the situation of the elements adjacent to the welded joint, we chose and stored their data. Fig 5-21 shows these elements. The elements are chosen from flyer plate and base plate at the interaction moment and at the collision point, and then are drawn the equivalent plastic strain and maximum shear stress graphs.
Fig. 5-21: PEEQ-Equivalent plastic strain for Flyer element, No.1) Grooved method, Time = (45 μs), No.2) Simple method, Time = (40 μs)

Fig. 5-22: shear stress near the contact point
No.1) Grooved method, Time = (45 μs), No.2) Simple method, Time = (40 μs)
Table 5-9: Equivalent plastic strain (PEEQ) of elements near the contact zone for flyer plate – grooved method

<table>
<thead>
<tr>
<th>Flyer plate width [m]</th>
<th>Flyer-PEEQ [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.146488</td>
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<tr>
<td>0.003</td>
<td>0.105742</td>
</tr>
<tr>
<td>0.006</td>
<td>0.108974</td>
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<tr>
<td>0.009</td>
<td>0.100442</td>
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<tr>
<td>0.012</td>
<td>0.100961</td>
</tr>
<tr>
<td>0.015</td>
<td>0.101276</td>
</tr>
<tr>
<td>0.019</td>
<td>0.103456</td>
</tr>
<tr>
<td>0.021</td>
<td>0.105895</td>
</tr>
<tr>
<td>0.023</td>
<td>0.102868</td>
</tr>
<tr>
<td>0.028</td>
<td>0.163052</td>
</tr>
</tbody>
</table>

Table 5-10: Shear stress (S12) of elements near the contact zone for flyer and base-plate – grooved method

| Flyer plate width [m] | Flyer-S12 [Pa] | Base-S12 [Pa] |
|-----------------------|-----------------|
| 0                     | 12457200        | -1.87E+07     |
| 0.003                 | -5681870        |                |
| 0.006                 | -31870300       | 3.00E+07      |
| 0.009                 | -6.69E+06       |                |
| 0.012                 | -9473980        | 3.52E+07      |
| 0.015                 | -1.91E+07       |                |
| 0.019                 | -1.42E+06       |                |
| 0.021                 | -33058200       | 3.82E+07      |
| 0.023                 | -33058200       | 3.37E+07      |
| 0.028                 | 56310500        | -2.16E+07     |

Table 5-11: Equivalent plastic strain (PEEQ) of elements near the contact zone for flyer plate – simple method

<table>
<thead>
<tr>
<th>Flyer plate width [m]</th>
<th>Flyer-PEEQ [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.075</td>
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<td>0.003</td>
<td>0.079364</td>
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<td>0.006</td>
<td>0.086288</td>
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<td>0.105525</td>
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<td>0.100726</td>
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<tr>
<td>0.015</td>
<td>0.102313</td>
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<tr>
<td>0.018</td>
<td>0.111978</td>
</tr>
<tr>
<td>0.021</td>
<td>0.105224</td>
</tr>
<tr>
<td>0.024</td>
<td>0.110272</td>
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<tr>
<td>0.027</td>
<td>0.105353</td>
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<td>0.106897</td>
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<td>0.033</td>
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<td>0.036</td>
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<td>0.039</td>
<td>0.104268</td>
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<td>0.042</td>
<td>0.101049</td>
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<td>0.045</td>
<td>0.079892</td>
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<td>0.047</td>
<td>0.078374</td>
</tr>
<tr>
<td>0.05</td>
<td>0.075</td>
</tr>
</tbody>
</table>
Stages 6&7
The required data and figures are derived from the software and used for drawing the corresponding curves. Table 5-9 shows an example of the data extraction for Equivalent plastic strain (PEEQ) of elements near the contact zone for flyer plate – grooved method and Table 5-10 shows shear stress (S12) of elements near the contact zone for flyer and base- plate – simple method. Table 5-11 shows an example of the data extraction for Equivalent plastic strain (PEEQ) of elements near the contact zone for flyer plate – simple method and Table 5-12 shows shear stress (S12) of elements near the contact zone for flyer and base- plate.

Table 5-12: Shear stress (S12) of elements near the contact zone for flyer and base- plate – simple method

<table>
<thead>
<tr>
<th>Flyer plate Width [m]</th>
<th>Flyer-S12 [Pa]</th>
<th>Base-S12 [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1.7E+07</td>
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</tr>
<tr>
<td>0.003</td>
<td>-129543000</td>
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<tr>
<td>0.006</td>
<td>-134886000</td>
<td>-1E+08</td>
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<tr>
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<td>-122254000</td>
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</tr>
<tr>
<td>0.012</td>
<td>81502700</td>
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<td>0.015</td>
<td>31617700</td>
<td>-5.3E+07</td>
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<tr>
<td>0.018</td>
<td>63397100</td>
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</tr>
<tr>
<td>0.02</td>
<td>4.03E+06</td>
<td>-5.2E+07</td>
</tr>
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<td>0.025</td>
<td>1.70E+07</td>
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<td>0.036</td>
<td>8920590</td>
<td>-4.7E+07</td>
</tr>
<tr>
<td>0.041</td>
<td>-86611800</td>
<td>-8.9E+07</td>
</tr>
</tbody>
</table>

Stage 8
It is now desired to compare the bonding quality between the simple method and improved groove method. (Al-Hassani & Akbari Mousavi, 2008) proposed two criteria for successful bonding in the explosive welding process. These criteria which are proposed for numerical simulation are as below:

1- Plastic strain criteria:
A threshold value of effective strain for bonding to take place should exist for different combinations of materials. It appeared that an effective strain higher than 0.35 was required for bonding of stainless steel to steel plates. For titanium to mild steel it was slightly lower at 0.25. The plastic strain was lower for the non-bonded case than that for the bonded case.

2- Shear stress criteria
The shear stresses in the two plates would have different sign (i.e. in opposite direction) magnitudes for bonding to occur whereas the shear stresses would have the same sign if bonding did not occur. So for an acceptable welded plate the sign of maximum shear stress in flyer plate must be of the opposite sign of the maximum shear stress in base plate.

Fig. 5-23 No. 1, 2 shows the effective strain profiles in the flyer for simple and grooves method. The strain levels were highest in the areas in which welding took place. The figure suggests that the lowest value of effective strain required for bonding to take place is of the order of 0.1.

Shear stress profiles are plotted in Fig.5-23 No.3, 4 for the simple method and improved groove method, respectively. According to No.3, in the edges where bonding did not take place, the stresses are of the same sign. Whereas the shear stress in the flyer plate and base plate were of opposite sign in
all regions in the case of improved groove method. We study this problem and its effect on the quality of joint in the next chapter.

<table>
<thead>
<tr>
<th>NO.</th>
<th>Contour Name</th>
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</tr>
</thead>
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<tr>
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</tr>
<tr>
<td></td>
<td>Simple</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Effective Plastic Strain</td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td>Grooved</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Shear Stress</td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td>Simple</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Shear Stress</td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td>Grooved</td>
<td></td>
</tr>
</tbody>
</table>

Fig.5-23: Effective Plastic Strain and Shear Stress
No. 1) Effective strain profiles in flyer for simple method,
No. 2) Effective strain profiles in flyer for grooved method,
No. 3) Shear stress profiles for simple method,
No. 4) Shear stress profiles for grooved method

Stage 9
The simulations provided graphical output showing contour maps and profiles of a number of physical parameters, such as contact pressure, normal stress, plastic strain, shear stress, effective strain, internal energy, strain rate, kinetic energy, temperature and velocity of the flyer plate at the point of contact and the angle of contact. Fig. 5-24 and 5-25 show some typical output of ABAQUS software.
Fig. 5-24: Results of simulation
No.1) JCCRT-Johnson-Cook plastic strain contour for flyer plate, simple method, Time = (59 μs),
No.2) S22 - Normal stress contour - simple method, Time = (40 μs)

Fig. 5-25: Results of simulation:
No.1) P-Pressure-Contour - Maximum pressure in simple method, Time = (40 μs),
No.2) P-Uniformly distributed pressure load on flyer plate in grooved model, Time = (45 μs)
6 Discussion

6.1 Impact-echo discussion

The method has potentials and limitations. The wave interference and its effect on the results are among the most important limitations of this method for using in dimensional measurements. In dimensional measurement, repeatability is the most important factor. Despite all of my efforts I could bring little development to this method and more research must be performed to further enhance its application in the industry.

6.1.1 Discussion on thickness measurement results

Concrete plate

- The FFT can be employed to determine a frequency analysis on the time-domain data. The resulting amplitude-frequency curves are more suitable than the displacement-time curves, and the necessary information such as the thickness of the concrete plate or the location of the cracks can be captured more accurately. In a concrete plate structure, the dominant peak in the spectrum determines the thickness frequency that is used to calculate the thickness of the structure as stated in equation (2.29). Fig. 5-5 shows that with the numerical response of a 150 mm thick plate, the dominant frequency of 12.72 KHz can be obtained. These results are in accordance with the corresponding results from the work of Chia-Chi.et al. (2007).

- To explain the effect of the impacting object–receiver distance on the thickness-amplitude, the time-history of nodal vertical displacements at various r/T ratios of the designed models are recorded (Chiamen, 2008). If the transducer is very close to the impacting object location, then the P-wave does not have sufficient time to separate from the S- and R-waves before it reaches the transducer. In addition, the impact can separate the transducer from the surface of the plate. In contrast, if the transducer is far from the impacting object location, then P-wave reflections from the plate bottom surface may disturb the integrity of the R-wave. For this reason, a ratio of r/T=0.3 (according to the previous study (Chia-Chi.et al., 2007)) was chosen to compensate for both of the aforementioned effects. This ratio ensures that the amplitude of the displacements caused by the P-wave arrival at the transducer is strong enough for the arrival to be easily identified. Figs. 5-4 through 5-11 show the results for nodes located at r/T=0.3.

- The analysis presented in this research assumes that the velocity of wave propagation in the concrete is equal to 4000 m/s. Therefore, the value of $\beta$ is calculated from equation (2.29) and found to be equal to 0.954. Thus, equation (2.30) can be written as follows:

\[
T = \frac{0.954C_p}{2\pi} \tag{6.1}
\]

- Figs 5-4 through 5-11 show that the amplitudes of direct and indirect tests are different from one another because the impacting object velocity is different in each method. Also, in the indirect method, the steel bar causes a decrease in amplitude. Therefore, increasing the impacting object velocity in the indirect method allowed the impact waves to gain sufficient energy to pass through the steel bar and propagate in the concrete plate. The amount of
increase in the velocity depends on the response of frequency, but to some degree it is obtained from experience. In this model the velocity of impacting object in the indirect method was chosen 2-3 times greater than the direct method. In spite of this amplitude difference, the resulting thickness frequencies are precisely the same in both the direct and indirect methods. This similarity implies that the thickness frequency is independent of the energy of the input wave.

- The indifference between the thickness frequencies obtained from the direct and indirect methods shows that the indirect method can be used to measure the thickness of plate-like structures.

- Table 5-3 summarizes the overall results of figures 5-3 to 5-5. The difference between the measured and the actual thickness is reflected in the last column of the Table. These values are calculated by dividing the difference between the measured and the actual thickness by the actual thickness of the plate \( T_l - T \). These negligible differences can be related to the computational and modelling errors.

- The two tables 5-4 and 5-5 show that the result of thickness measurement for 2 typical direct and indirect methods is the same, and simulation results are verified by the experiments. The difference between actual and experimental thickness measurement occurred because of concrete specifications.

Steel plate

- In our analyses we consider the velocity of wave propagation in the steel equal to 6020.18 m/s. Therefore the value of \( \beta \) is calculated from equation (2.29) to be equal to 0.93. \( \beta \) is a shape factor and it depends to material, therefore \( \beta \) for concrete is different from \( \beta \) for steel.

- It can be seen from figures 5-7 to 5-11 that in each of these graphs the amplitudes are different from one another. This is because the impacting object velocity and the plate thicknesses vary. Therefore, we increased the impacting object velocity in order for the impact waves to gain enough energy to pass through the steel plate. The thickness frequency is independent of the energy of the input wave, a fact that is in accordance with the findings from previous studies (Chia-Chi et al. 2007) and (Chiamen, 2008). The accordance between the thickness frequencies obtained in this study for different thicknesses of steel plate shows that the impact echo method can be used throughout to measure the thickness of steel plates. The difference between measured and actual thickness is reflected in the last column of Table 5-6. These values are calculated by dividing the difference between measured and actual thickness by the actual thickness of the plate \( \frac{T_l - T}{T} \). These negligible differences are no indication of any specific trends and can be related to the computational and modelling errors.

6.1.2 Discussion on wave propagation results

Wave propagation along the bar and plate and the corresponding reflections

- Figures 5-13 to 5-15 show how the impact wave propagates through the bar and plate and the corresponding reflections with assuming perfect contact between rod and concrete. Step 25 shows when the wave is in its initial propagation phase in the steel bar while the concrete
place has not received any pulse. This step also shows that the direction of wave propagation and the direction of particle movement are the same. The counter bar shows that the stress waves are of the compressive type during this period of time. Step 80 shows the entrance of the stress waves into the concrete plate, and the waves remain compressive. Steps 85 through 156 indicate that some of the stress waves are refracted into the concrete plate and that some are reflected as a compressive pulse in the steel bar. At the interface between the steel bar and the concrete plate, the angle of incidence is 90°. Thus, the ratio of amplitude of the refracted wave to the amplitude of particle motion in the incident wave can be obtained as follows (Sansalone & Streett, 1997):

$$R_{\text{refracted}} = \frac{2Z_c}{Z_c + Z_s} \quad (6.1)$$

Where $Z_c$ and $Z_s$ are the acoustic impedances of the concrete and steel, respectively. The acoustic impedance $Z$ is the product of the wave speed and density of the material. Equation (3.1) gives $Z_c = 92 \times 10^5$ and $Z_s = 470 \times 10^5$. Therefore, the value of $R_{\text{refracted}}$ is calculated to be 33%. Thus, the amplitude of the reflected wave to the amplitude of particle motion is approximately 67%. For this reason, the energy of the impacting object must be greater in the indirect method than in the direct method for the refracted wave to have sufficient energy to propagate and reflect through the media. The reflected wave from the interface remains unchanged in shape, i.e., the reflected wave in the bar is still compressive. This phenomenon can be observed from the counter bar in steps 85 to 156 in which all the displacements have negative signs.

Step 158 shows that the wave, after reaching the free end of the bar, undergoes a total reflection because there is air at the other side of the interface. The reflection is due to the difference in impedance between steel and air (the acoustic impedance of air is approximately 0.4). Steps 158 to 230 show waves having a tensile shape. Thus, in step 230, a wave enters the concrete plate with a tensile shape and reflects a tensile shape without any change in the displacement sign in the steel bar. The counter bar in step 230 shows that most of the displacements have positive signs. From step 230 to 300, the reflected wave in the bar is tensile, and the corresponding displacement signs in the bar have positive signs. These results are in accordance with the theory of reflections of stress wave from free-ended and not free-ended bars (Johanson, 1970).

Steps 80, 230 in Figs. 5-13, 15 show that in the indirect method the stress waves transmit through the concrete plate several times after the impact on the bar. However, in the direct method, these stress waves only transmit once.

**Evaluation of plate thickness**

- The spherical wave fronts in Fig. 5-12a show how the P-wave and S-wave propagate through the solid. This figure shows that when the P-wave reaches the bottom of the plate, the S-wave is only halfway to the bottom. Fig. 5-12b shows that when the reflection of the P-wave is halfway up the plate, the S-wave reaches the bottom of the plate. This pattern is in accordance with what has been reported by Sansalone and Streett (Sansalone & Streett, 1997).

**Other applications**

- In the thesis we applied the indirect impact-echo to measuring the thickness, but studies and experiments have shown that the impact-echo method is effective for locating voids, delaminations honeycombing, depth of surface opening cracks, and measuring thicknesses (Sansalone, M., 1997). Consequently, the indirect method could be used to locating voids and cracks and the other inspection applications.
6.2 Discussion on explosive welding results

Despite its limitations, EXW method has found no replacement in specific applications. It is proposed new techniques in the explosive welding process and the results were evaluated. Some experiments have been done in the licentiate period and I refer the reader to the licentiate book for a discussion on those results (Tabatabae Ghomi, 2009). In this section the results of experiments and performed simulations are briefly discussed. The results include experiments and developed simulations on the unequal surface jointing of aluminium and copper plates that was stated in the previous section.

6.2.1 Discussion on experiments

Requirements for successful bonding

- The main parameters $a, \beta, V_d, V_p, V_f, V_c, A , WW$ diagrams, and quality tests including peel off test, TBS, SEM, were measured and are described in the licentiate thesis with more details (Tabatabae Ghomi, 2009).

- Suitable setups for successful bonding can be identified through tests to measure various variables. Like a series of carriages that make up a train, a series of diagrams can be constructed, and the welding window in this composite diagram describes the test space where a successful weld can occur. In the absence of this composite diagram, it is assumed that the most pertinent relationship is the one between the pressure $P$, the impact velocity $V_e$, base plate velocity $V_p$, and the effective strain. The flyer plate attains its peak velocity at the collision point. On impact the velocity of the base plate at the collision point increases while the flyer plate velocity decreases. Under certain conditions, the velocities of the flyer and the base plate are the same. When the situation stabilizes at the collision point and the pressure is high, inter-atomic bonding occurs (See licentiate booklet (Tabatabae Ghomi, 2009)).

- If there is sufficient velocity difference across the interface between two fluid surfaces of different density Kelvin-Helmholtz instability may arise. The instability produces a wavy shape at the interface as shown in Fig. 6-1a. The wavy shape is similar to the shape that illustrated in Fig. 2-12 e.

- Metals welded by explosive preferably exhibit a wavy bond zone interface. The wavy bond is remarkable because of its very regular shape. Bond zone wave formation is similar to that of a fluid flowing around an obstacle. When the fluid velocity is low the fluid flows smoothly around the obstacle; above a certain velocity, the flow pattern becomes turbulent. Because the pressures in this region are many times higher than the yield strength of the metals, they flow plastically in a manner like fluids. The microstructure of the metals at the interface shows clearly that the metals did not melt but flowed plastically during the process. SEM investigation showed that no diffusion occurred due to extremely rapid self-quenching of the metals. The bond shows the frozen flow shape of the plastic metal flow during bond creation (Fig. 6-1a).

- Fig. 6-1b shows an explosion welding interface between Al and Cu. Under the curl of the waves, small pockets of solidified melt may be seen. Some of the kinetic energy of the flyer plate was locally converted into heat in these pockets as the system came to rest. The quality of welding is related to distribution and size a of solidified melt pockets at the collision point.
The pockets of solidified melt along the interface are brittle and contain localized defects that do not, however, seem to affect compound properties.

- When the collision velocity is high, some cladding metals develop thermal adiabatic shear bands at the interface. The shear bands can lead to shear cracks that enter the cladding surface. However, such cracks can keep hidden under the clad surface or at the interface as shown in Fig. 6-1c. When the collision energy and welding conditions are optimal, thermal shear bands are minimized, and shear cracks can be avoided.

![Fig. 6-1: Metallographic test for an Al-Cu successful bonding, Grooved method](image)

**Stage 1**

- The overall shape of experiments for both (simple and grooved method) are the same, and at the first time there was no difference between them. The requirement tests included SEM investigation chisel test, tensile test of samples from the welding window and measurements of detonation velocity and are described in the licentiate thesis (Tabatabaee Ghomi, 2009).

**Stage 2**

- TBS were measured in two directions. These tests showed that the Tensile Bond Stregths were constant in the improved test with grooves surrounding the contact surface. Fig. 5-17 shows the result in two directions. In experiments using surfaces without grooves, TBS is very low at the edges and increases towards the middle of the welding area. The curves show that the strength reaches the maximum value within 1 to 1.5 times the thickness of the flyer plate from the edge. In the improved grooves test the edges were uniform and produced suitable joints after jumping. The mechanical tests show that the grooved method is suitable for joining two metals with different surfaces and does not give any edge strength problem.

**6.2.1 Discussion on simulation results**

**Stage 3**

- The model was run for the simple method and for several depths of grooves in the grooved method. The explosive material in the model was chosen similar to material in the experiments, with the same detonation velocity.
• For the grooved flyer plate, when the collision takes place, the damage parameter D (equation 3.4) exceeds unity in the elements located at the grooves and the edges will be cut off beyond the groove. Fig.5-18 shows the Johnson-Cook damage initiation criterion at integration points after explosion. It is clear from this figure that the damage criterion has high values on the grooves.

Stage 4

• The model was run for simple method and several depths of grooves (1, 2, 3, 4 mm depth). At the end of the running of the software the best depth for separation was found to be 4 mm of the flyer plate depth (see Table 5-8 No.5&6). The final step of the separation of two parts is illustrated in Fig. 5-19.

Stages 5, 6, 7

• For evaluating the results, Johnson-cook plastic strain, effective plastic strain and maximum shear stress contour were plotted. Fig 5-20 No.1 shows the Johnson-Cook plastic strain contour hardening and failure criteria parameters for the flyer plate. The damage originated from the grooves. Fig 5-20 No. 2 shows maximum shear stress of the flyer plate in the grooved model. According the figure the highest shear stress was occurred at the collision point and on the part 2 (see Fig. 5-19) and in separated part the normal stress was less than the other collision point. Fig.5-21 shows the equivalent plastic strain for a flyer element near the collision point zone. Fig.5-21No.1 is an element group in a line near the collision zone for grooved method at the final step. The figure shows that the plastic strain was increased near the grooves. Fig.5-21 No.2 is an element group in a line near the collision zone for the simple method at the final step. The figure shows that the maximum shear stress was decreased near the edges.

• Fig 5-22 shows maximum shear stress for flyer and base plate elements near the collision point zone. Fig 5-22 No.1 is an element group in a line near the collision zone for grooved method at the final step. The figure shows that the maximum shear stress occurred at the middle. Fig 5-22 No.2 is an element group in a line near the collision zone for simple method at the final step. The figure shows that the maximum shear stress was increased at the middle of flyer plate.

Stage 8

• Fig.5-23 No.1 shows the effective strain profiles in the flyer plate for the simple method. The strain levels were highest in the areas in which welding took place. The figure suggests that the lowest value of effective strain required for bonding to take place is of the order of 0.1. The simulations predicted a lower value of effective strain for the non-bonded edges. In the case of the improved groove method, the effective strain profile in the flyer plate shows that the strain levels were higher than 0.1 in the all of the area to be welded. This result is shown in Fig.5-23 No.2.

Shear stress profiles are plotted in Fig. 5-23 No. 3 & 4 for the simple method and improved groove method, respectively. According to the figure, in the edges where bonding did not take place, the shear stresses are of the same sign. Whereas the shear stress in the flyer plate and base plate were of opposite sign in the all regions in the case of improved groove method. According to the Fig. 5-23 No.4 successful bonding takes place between flyer and base plate using improved groove method.

• However the velocities parallel to shear velocities must have different signs in order for bonding to occur, and at the interface shear stress becomes negligible (the combination of two different sign reach to zero at the collision point) compared to the pressure and the metals will
behave like fluids. For bonding to occur the flyer plate and the base plate must have a relative velocity in the impact region, therefore the conditions for certain of a Kelvin-Helmholtz instability are fulfilled. Fig. 5-23 No.4 shows that the successful bonding was accrued according to the Kelvin-Helmholtz theory. The instability produced wavy shape at the interface is illustrated in Fig. 6-1.

Stage 9

- The Johnson-Cook plastic strain contour hardening for the flyer plate-simple method in Fig. 5-24 No.1 shows the edge problem and verified the subject of Tensile Bond Strength in the theory section (See Fig.2-13 d).
- Fig. 5-24 No.2 shows the normal stress contour in simple method. In both methods the highest stress predicted was at the collision.
- Fig. 5-25 No.1 shows the maximum pressure contour in simple method. In both methods the highest pressure predicted was at the collision.
- Fig. 5-25 No.2 shows distributed pressure load on flyer plate in grooved model. The uniform shape of the impact wave and maximum pressure at the collision was indicated.

6.2.3 Discussion on energy consumption

Simulations suggested the best depth and location of grooves, then optimized by simulation and experiment. In the experimental results TBS is related to transition of electricity in Al-Cu joints. Although measuring of electricity resistance of the joints was not in the scope of this thesis, the grooved method has a straight influence to reduce the energy consumption. The amount of energy consumption must be measured in the factory. Reduction of electric energy consumption could be estimated at 21% by calculating the difference between the areas under the curves that illustrated on the Fig.5-17, and the area is estimated according the Fig 6.2. The calculation is as follows:

\[
\frac{148 \times 49}{142 \times 42} = 1.21
\]

Fig 6.2: The areas under the curves according to Fig.5-17
7 Conclusions

The primary objective of this work was further development in process of the elastic and plastic impact wave methods aiming to reduce the energy consumption of the explosive welding (EXW) as well as cost reduction associated with NDT technologies.

The impact energy wave creates elastic deformation that moves the particles of the body. In this research we focused on the dimensional measurement by calculating the time of wave travel between the source of energy and a discontinuity in the part. The impact echo (IE) method can be used for determining the location and extent of concrete and other structures. In this study we introduced a new indirect method for thickness measurement of concrete plates, which is applicable where there is not appropriate access to either of the plate surface. Simulation of the impact-echo method was carried out numerically using LS-DYNA software.

An impact wave of high energy produces plastic deformations in metals. In this research, explosive welding has been studied. A new method for joining metals with unequal surfaces for Al-Cu based material has been introduced. A large amount of 3-D numerical simulations have been performed using ABAQUS/Explicit commercial software.

Some objectives of this research were achieved in the first part of the project and are covered in detail in the licentiate thesis (Tabatabae Ghomi, 2009)). In that thesis we proposed some new methods by conducting tests on flat surfaces and pipes. In this part of research we present new techniques in the NDT and EXW fields for achieving our objectives by using modelling and simulation tools. The improvements achieved in these fields are summarized as follows:

1. Introducing a new indirect method in impact-echo
2. Introducing a new solution for measuring the thickness of steel plate in impact-echo
3. Introducing a new Grooved method for unequal surface in EXW
4. Introducing a new vertical and dual method for unequal surface in EXW (Licentiate Thesis)
5. Introducing a new method for removing leakage of metal pipes in EXW (Licentiate Thesis)

The effect of each of the above improvements on the reduction of energy consumption and cost is summarized in Table 6-1.

<table>
<thead>
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<th>No.</th>
<th>Improvement</th>
<th>Field/Application</th>
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<th>Cost reduction</th>
<th>Paper</th>
<th>Patent Ability</th>
<th>Industry commercialize</th>
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<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>5</td>
<td>Remove leakage</td>
<td>Plastic/EXW</td>
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<td>✓</td>
<td>✓</td>
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</tr>
</tbody>
</table>

Table 6-1: Conclusion of the research work on improvement of impact waves application
7.1 Impact-echo conclusions

The finite element study of the Impact-Echo method is implemented successfully for determining the thickness of concrete plates using the indirect method. The results are validated by comparison to the direct method. In the indirect method we use a steel bar to transmit the stress waves from a steel ball impacting object to the surface of a concrete plate that is not fully accessible. For this purpose we need to access the surface of the concrete plate only at two points: one for installing the steel bar and the other for mounting the transducer. This method has apparent advantages over the direct measurement method for inaccessible structures. This study can provide a basis for full version modelling of a buried plate under soil. The results obtained are completely consistent with the direct method and can be used to measure the thickness of concrete-plate structures where there is limited access to the surface of the plate. The numerical calculations proved to be an invaluable tool for better understanding of the Impact-Echo method, for determination of the physical possibilities and limits of the method as well as for development of NDT methods. The most important conclusions of this thesis are as follows:

- **Introducing a new indirect method in impact-echo method**: For thickness measurement of concrete plates, which is applicable where there isn’t appropriate access to each of the plate surfaces.

- **The indirect method will reduce the cost of measuring process**: This will happen by reducing the time of testing and instrumentation of process.

- **Frequency, amplitude, and wave shapes in concrete and steel plate were investigated.**

- **The shape factors in concrete and steel plate were obtained.** The value of $\beta$ was equal to 0.954 for concrete plate and 0.93 for steel plate.

- **Modelling and simulation of IE method and using a ball as an impacting object**

- **FFT in MATLAB**: by using Fast Fourier Transformations (FFT) we carried out a frequency analysis on the time-domain data.

- **Simulation results were confirmed by experiments**

- **The reflection of waves was investigated.**

- **Introducing a new solution for measuring the thickness of steel plate**: The impact-echo method is often using for concrete structures. The results of this study indicate that this method also could be report truly the thickness of the steel plates.

7.2 Explosive welding conclusions

As described in this thesis, it is possible to join two or more metal parts using impact waves. When explosive materials are used to generate the necessary impact, the process is called explosive welding (EXW). This method does not require a heat source and no (or very localized) melt is created during the process. The interface temperature throughout the process is usually lower than the melting points of either material. EXW does not have the common problems of welding at the contact point and with suitable control of the process parameters during the test the weld will be of the high quality. These process parameters are predictable and measurable. There are some limitations in EXW at present and its use in mass production is still in its infancy. This method covers a multidisciplinary research area,
many results have been reported, and many theoretical and numerical methods have been invented in the last few decades. A number of numerical software packages were used to analyse the process but complete simulation of EXW process is not yet possible. The most important conclusions of this thesis are as follows:

- **A new method in explosive welding of unequal surfaces was presented:** In this way making grooves on the flyer plate was suggested. The influence of this method was shown using experimental and numerical analysis. Experimental results showed the effectiveness of this method. The numerical results had also good agreement with the experimental results. The numerical results showed the accuracy of criteria suggested by (Al-Hassani & Akbari Mousavi, 2008). The major result of these experiments was the discovery of a suitable solution for obtaining uniform contact in explosive welding of two metals of unequal surfaces. The solution to the problem was the use of grooves on the flyer plates which led to shedding of the edges during the test. The efficiency of this idea was verified by the mechanical tests and the results of simulations.

- **The EXW joining of Cu–Al was successful and no fault was formed at the interface:** This was verified by SEM testing and also by the mechanical tests defined in the theory section. This part was described in the licentiate thesis (Tabatabaei Ghomi, 2009).

- **Simulation results confirmed the edge problem:** The groove model is suggested according to simulation results. The modelling and simulation of explosive welding was made by ABAQUS software and the results were compared to the actual values. The simulations suggest that the lowest value of effective strain required for bonding to take place is of the order of 0.1.

- **Process development:** The best depth of grooves (4 mm) was optimized by simulations and experiments.

- **Reducing energy consumption:** Reducing of electricity energy consumption could be estimated to be around 21% during production in an aluminum factory.

- **Commercialization:** The results of this thesis are being used in an aluminium factory. Unequal Al–Cu joints are used to transmit the electric power to anode rods. As a result of this thesis, more than 1000 successful EXW joints have been made and confirmed by the factory.

- **The EXW conclusions in Licentiate Thesis:** The following achievements were introduced in the licentiate thesis:
  - Introducing a new vertical and dual method for unequal surfaces
  - Introducing a new method for removing leakage of metal pipes

### 7.3 Future work

Although much work has been done on the impact wave energy, this is an extensive area of research that has the potential for further development and research. Some future possible work in this area is proposed in the following passages.

- **Future work on elastic part of impact waves**
  - Ultrasonic waves
  - Measurement by impact waves

- **Future work on impact-echo**
  - Measuring pipe thicknesses
  - Measuring pipe and rod length under the sea
- Inspection of railways
- Length measurement by impact-echo method

- **Future work on plastic zone of impact waves**
  - Forming and shaping of metals
  - Deep drawing
  - Powder metallurgy

- **Future work on explosive welding**
  - Underwater EXW experiments.
  - EXW on pressurized pipes.
  - EXW on large surfaces with unequal surface areas.
  - EXW on special multilayer surfaces.
  - Other applications of EXW such as special cladding and stress relieving.

### 7.4 Practical output of the thesis

In the usual impact-echo method for measuring the thickness of a concrete plate, there must be direct access to one of the surfaces of the plate under test. In buried plates there is no access to any of the surfaces, so this method cannot be applied. In this study we proposed an indirect measurement method that uses a steel bar to transmit the impact signal to the concrete plate. Thus, using this method we can test a concrete plate only with access to a small point of the surface of the plate. This study can provide a basis for full modelling of buried plated under soil. The results obtained are completely consistent with the direct method and can be used thoroughly to measure the thickness of concrete-plate structures where there is limited access to the surface of the plate.

Aluminium, copper, and steel are the most common metals used in high-current conductor systems. Use of these metals in dissimilar metal systems often maximizes the effects of special properties of each material. However, joints between incompatible metals must be electrically effective to minimize power losses. Mechanical connections that include aluminium create high resistance because of the presence of the self-healing oxide skin on the aluminium component. Because this oxide layer is removed by the jet in EXW, the interface of an explosion-clad aluminium assembly offers no resistance to the current. The results of this thesis are being used in the ALMAHDI aluminium factory, a large producer of aluminium (200,000 tons/year) in the southern Iran. Unequal Al–Cu joints are used to transmit the electric power of anode rods in this factory, and are shown in Fig.7-1.

![Fig.7-1: Al–Cu joints transmit the electric power to anode rods in the aluminium factory](image-url)
Bibliography


Onzawa, T. et al., 1985. Microstructure of explosively bonded interface between titanium and very low carbon steel as observed by TEM.


