APPLICATIONS OF THE ANFIS AND LR MODELS IN THE PREDICTION OF SHEAR CONNECTION IN COMPOSITE BEAMS

ALI TOGHROLI

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ABSTRACT

Channel connectors are fairly new alternatives to the shear connectors. Due to their complex behavior and lack of valid approaches, the prediction of shear capacity of these shear connectors is very difficult. The conventional push-out tests and simple modelling of these connectors provide limited guidance in their structural behavior and the results are valid only for the selected testing protocol. Recent advancements in the area of Artificial Intelligence (AI) have made it feasible to utilize the application of these technologies in the construction industry and structural analysis. Particularly, the use of Artificial Neural Networks (ANNs) has been widely accepted as a reliable tool to solve complex problems in an accurate way. The collective behavior of an ANNs is like a human brain that demonstrates the ability to learn, recall and generalize from training patterns or data. A sub-type of ANNs is Adaptive neuro fuzzy inference system (ANFIS). It integrates both neural networks and fuzzy logic principles with a potential to capture the benefits of both in a single framework. This study aims at predicting the shear strength of channel shear connectors in composite beam comprised of steel and concrete sections using ANFIS as a non-linear modelling tool and the classical Linear Regression (LR) as a linear modelling tool. A set of 1200 experimental data is collected till date and used as an input data of the push-out tests and the output data being the corresponding shear strength which were recorded at all loading stages. The results derived from the use of ANFIS and the LR was then compared. The outcome shows that the use of ANFIS produces highly accurate, precise and satisfactory results as compared to LR. Afterwards, ANFIS network was used to determine which parameters are the most influential on shear strength of channel shear connectors. Two output parameters were analysed, namely load per connector and slip of the shear connectors. To assess the shear strength of channel shear connectors, it is desirable to select and analyse

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factors or parameters that are truly relevant or the most influential to the shear strength estimation and prediction. This procedure is typically called variable selection that corresponds to finding a subset of the full set of recorded variables that exhibits good predictive abilities. Variable searching using the ANFIS network was performed to determine how the selected parameters affect the shear strength.

ABSTRAK

Penyambung saluran alternatif adalah agak baru untuk penyambung ricih. Oleh kerana tingkah laku yang kompleks dan kekurangan pendekatan yang sahih, ramalan keupayaan ricih bagi penyambung ricih adalah sangat sukar. Ujian konvensional tolak keluar dan pemodelan mudah penyambung ini menyediakan panduan yang terhad ke atas tingkah laku struktur dan adalah sah hanya untuk protokol ujian yang dipilih. Kemajuan terkini dalam bidang Kepintaran Buatan (AI) telah membuat ia dilaksanakan untuk menggunakan aplikasi teknologi ini dalam industri pembinaan dan analisis struktur. Secara spesifik, penggunaan Rangkaian Neural Buatan (ANN) telah diterima secara meluas sebagai alat yang boleh dipercayai untuk menyelesaikan masalah yang kompleks dengan cara yang tepat. Kelakuan kolektif ANN, adalah seperti otak manusia yang menunjukkan keupayaan untuk belajar, ingat dan umum dari corak latihan atau data.Sub-jenis ANN adalah neuro penyesuaian sistem kesimpulan kabur (ANFIS). Ia menggabungkan kedua-dua rangkaian neural dan prinsip-prinsip logik kabur dengan potensi bagi mencapai faedah kedua-dua dalam satu rangka kerja. Kajian ini bertujuan untuk meramalkan kekuatan ricih penyambung saluran ricih dalam rasuk komposit mengandungi bahagian keluli dan konkrit dengan menggunakan ANFIS sebagai alat pemodelan bukan linear dan regresi linear klasik (LR) sebagai alat pemodelan linear. Satu set 1200 data eksperimen dikumpul sehingga tarikh dan digunakan sebagai data input ujian tolak keluar dan data output bersamaan dengan kekuatan ricih direkodkan pada semua peringkat pembebanan. Keputusan yang diperolehi daripada penggunaan ANFIS dan LR kemudiannya dibandingkan. Hasilnya menunjukkan bahawa penggunaan ANFIS menghasilkan keputusan yang sangat tepat, jitu dan memuaskan berbanding dengan LR. Kemudian, rangkaian ANFIS digunakan untuk menentukan parameter yang paling berpengaruh pada kekuatan ricih penyambung saluran ricih. Dua parameter output dianalisis, beban bagi setiap penyambung dan gelinciran penyambung

ricih. Untuk menilai kekuatan ricih penyambung saluran ricih, adalah wajar untuk memilih dan menganalisis faktor atau parameter yang benar-benar berkaitan atau yang paling berpengaruh untuk anggaran kekuatan ricih dan ramalan. Prosedur ini biasanya dipanggil pemilihan pembolehubah yang sepadan untuk mencari satu subset set penuh pembolehubah direkodkan yang mempamerkan kebolehan ramalan yang baik. Pencarian pembolehubah menggunakan rangkaian ANFIS yang telah dijalankan untuk menentukan bagaimana parameter terpilih memberi kesan kepada kekuatan ricih. Keputusan yang diperolehi menunjukkan bahawa kekuatan mampatan konkrit adalah yang paling berpengaruh untuk ramalan dan anggaran kekuatan ricih.

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CHAPTER 1: INTRODUCTION

1.1.   General

When steel and reinforced concrete are used separately they present some shortcomings and those shortcomings may increase the cost of the construction. For example, steel girders are fabricated using thin plates and as a result of that they are prone to local and lateral buckling as well as fatigue (Oehlers & Bradford, 1995). Also, the concrete sections are generally thick and unlikely to buckle. However, unlike their high strength in compression they present weak behaviour when they are subjected to tension. Despite these problems, combining steel and concrete in the right combination, which uses each other's positive attributes, brings advantages to both elements.
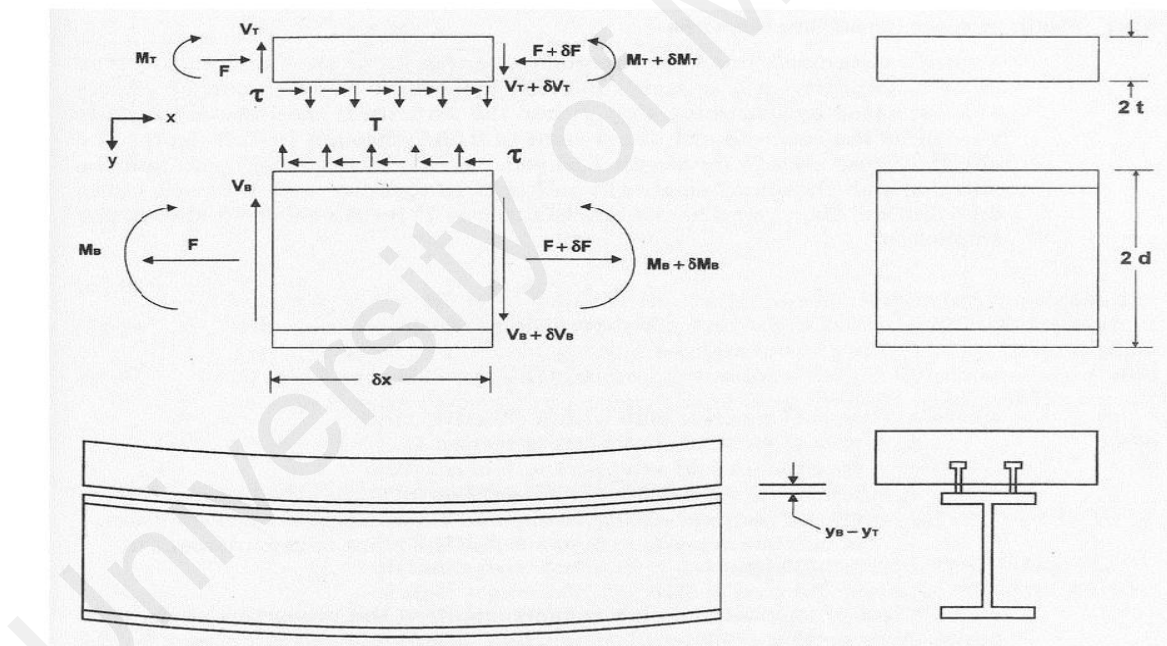
Figure 1.1: Forces Acting on a Composite Section (Viest et al., 1997)

Composite beams are generally assumed to be loaded in flexure (Figure 1.1). This creates such a condition that steel girder works in tension and the reinforced concrete deck works in compression. This working condition can only be made possible if the both the steel girder and reinforced concrete deck are connected intermittently so

that they can work as one. To transfer the horizontal shear force from the steel section to the reinforced concrete slab, several mechanisms can be utilized such as adhesion, friction and bearing (Viest et al., 1997).

The interaction of the steel section and the reinforced concrete is vitally important in composite structures. If we assume that there is no connection between two mediums; the applied flexural forces would be resisted by steel girder and concrete deck separately (Figure1.2).
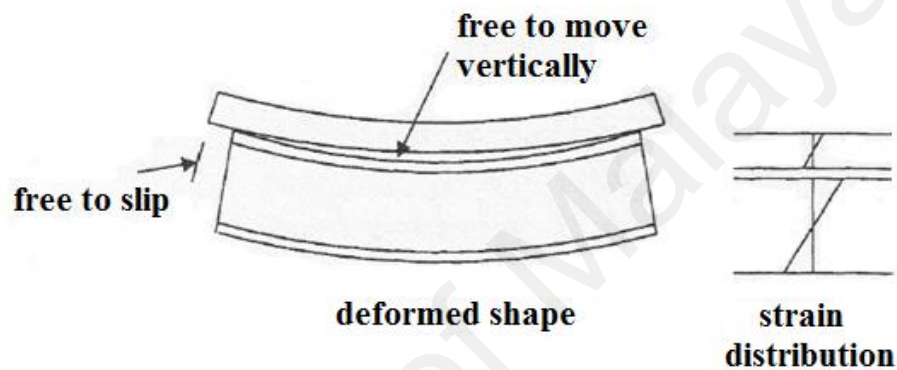
Figure 1.2: No Interaction (Viest et al., 1997)

In the most satisfactory case steel girder and the reinforced concrete deck would be connected and react as one member (Figure1.3). Under flexural loading, concrete is weak in tension so steel girder would provide the necessary tensile strength and with a minimum section depth concrete would carry the compression. The depth of the beam subjected to the increased flexure is now increased acting by itself so this would increase the flexural strength and stiffness of the section resulting in cost, making composite sections more economical and more efficient from other options.
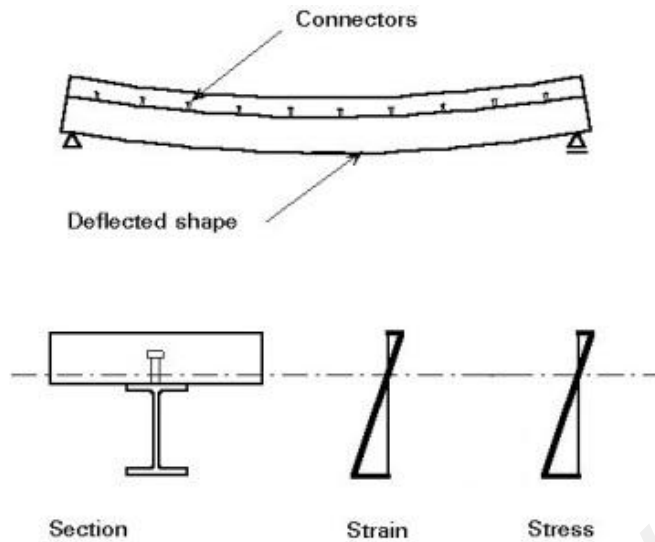
Figure 1.3: Complete Interaction (Viest et al., 1997)

1.2. Shear Connectors

A connection transmitting the shear forces in composite beams is considered as fully effective when no increase in the flexural strength of beam occurred with the addition of more shear connectors (Mistakidis et al, 1994). In most composite beams shear connection is provided using a steel member welded to the top flange of the steel girder and embedded in reinforced concrete. Those members transfer the forces between steel girder and the connector by shear and between connector and concrete by bearing (Viest et al., 1997). To be able to calculate the strength of the composite beam, designers should understand the quantitative behaviour and the strength of the shear connectors.

The structural capacity of a composite section depends on the efficiency of interaction among the elements. Shear connectors offer the essential interaction required for sufficient flexural strength and transmits the enormous longitudinal forces in the concrete to the key adjacent force sustaining member of the beam (Figure 1.4). In the event of seismic vibrations, these shear connectors experience reverse cyclic loading

(Hawkins & Mitchell, 1984). Together with the concrete element, shape, size and material properties of these shear connectors govern the composite behaviour of the structure (Valente & Cruz, 2004). The estimation of rigidity and flexibility of shear connectors depends upon the level of shear force distribution and operational efficiency between steel and concrete (Ranković & Drenić, 2002). The splitting strength of concrete determines the degree of resistance of concrete element covers the connector.
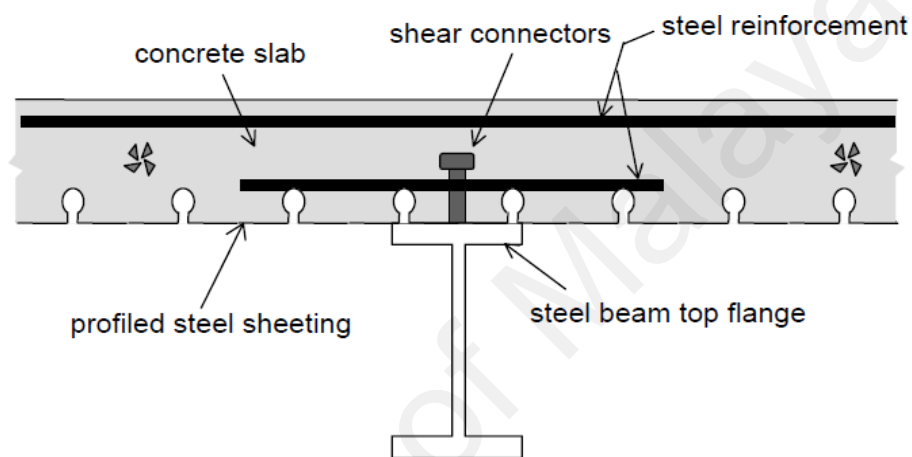
Figure 1.4: Typical stud shear connector (Valente & Cruz, 2004)

1.3.   Research Significance

The only knowledge about the behaviour and strength of the channel shear connectors is limited to the experimental information obtained from previous researches. However, experimental programs are costly and time consuming. These are the main disadvantages of alternative shear connector researches.

With the improvements toward mathematical modelling it is becoming more and more possible to use finite element models to simulate the experimental programs. On the other hand, there are still challenges with modelling concrete as a nonlinear material.

Due to expensive experimental tests and lengthy procedure of the non-linear finite element analysis, the estimation of shear strength of channel connectors in composite

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beam is rather difficult. In this research, the application of ANFIS as a non-linear tool and linear regression (LR) as a linear tool in predicting the shear capacity of channel connectors in composite beam are being examined and compared. The proposed model offers an adequate prediction of the strength of channel connectors with varying dimensions and in concrete with different strength level, with and without reinforcement bars.

This study provides a comparison of channel and angle connectors subjected to the experimental and parametric investigations. The investigation was carried out, to establish the behaviour of the channel shaped and angle shaped shear connectors, in reinforced concrete slabs and to compare their shear capacity, when the same size of them were used, in push-out tests. This study aims at examining the behaviour of channel shear connectors and the effects of their different sizes in concrete with varying strength levels, with and without reinforcement bars under monotonic and low cycle fatigue loading. However, since the casting, curing and testing procedures of channel shear connectors involved high costs, the search for new effective tools which are economical is required in designing shear connectors with modelling. Moreover, it is essential in determining the shear strength of shear connectors with varying dimensions and in different levels of concrete strength. This involves the utilization of modern models in predicting the channel connectors' shear capacity, emphasizing on their behaviour.

1.4. Objectives

The followings are the main objectives of this research:

1. To implement Artificial Intelligence approaches to investigate the behaviour of channel shear connectors.

2. To select the most influential parameters on shear strength of channel shear connectors by Artificial Intelligence approach.

3. To compare the effectiveness of Linear regression approach and Artificial Intelligence approach in determining the shear strength of channel connectors.

1.5. Scope

The following points cover the scope of this study:

1. Estimation of load-slip behavior of channel connectors through experimental investigations

2. Development of the ANFIS model with experimental data means web thickness, flange thickness, connector's length and concrete compression strength as an input and strength of shear connectors as an output.

3. Combine fuzzy logic and ANN approach model development based on the AI approach for the above purposes.

1.6. Thesis Layout

This study contains five chapters. The first chapter of this study provides introductory information about different types of shear connectors and their behavior, particularly focussing on the structural behavior of channel connectors. The details of testing recommended for connector testing is also defined. The information about AI, ANN, ANFIS and fuzzy logic approaches, their input and output data set detailing is also provided. The second chapter of this study provides a literature review of the studies focussing on channel connectors and different types of concrete used in composite beams along with channel shear connectors. A major failure modes and findings discovered by previous researchers are focused. The third chapter of this study defines the research methodology to achieve the objectives of this study. The

dimensional details of push-out specimens, the modelling of ANFIS and the LR models and the experimental arrangement adopted and simulated were defined in detail.

The fourth chapter explains the results obtained after testing and modelling. The major failure modes, explanation of load-slip behavior, comparison of experimental and ANFIS results and ANFIS and LA results are provided. The fifth chapter provides the summary and conclusion of this study together with future recommendations.

CHAPTER 2. LITERATURE REVIEW

2.1. General

Steel-concrete composite structures using normal weight concrete have been used since 1920 and there has been considerable use of composite structures for bridge construction from 1950 as a result of the research by (Viest, 1956; Viest et al., 1997; Viest & Elstner, 1956) investigated the behaviour of channel connectors used in composite beams. In total, forty-three push-out specimens divided in seven groups were tested. Principle variables were strength of concrete, dimensions of channel shear connectors, the restraint of concrete under the connector and the direction of load. These tests were designed to provide;

1. Information about the behaviour of channel shear connectors.

2. Insight for the effects of the mentioned variables on channel connector's behavior and load carrying capacity.

Test results showed that flange thickness, web thickness and length of the connector, had affected the behavior of the channel significantly. The orientation of load whether channel loaded from its back or front side did not make any mentionable effect on connector's behavior.

In 1957 for the revision of ASSTHO, semi empirical equations for a useful capacity of various mechanical shear connectors were developed. After this, in 1960, ASCE-ACI committee for composite construction retained the ASSTHO equations, but added a factor of safety for statically loaded members. These equations were satisfactory for structural safety perspective; however these do not provide economical solutions. Its main development in building structures in the last decade was an outcome of the basic design provisions introduced in the 1961 American Institute of Steel Construction (AISC) specification. The growth of these provisions was founded on

studies by (Slutter & Driscoll, 1965). Their study was the part of an investigation on ultimate strength capacities of composite steel and concrete beams. Throughout the study various types of mechanical shear connectors were tested and one of them was channel shear connector. The aim was to develop a criterion for minimum shear connector requirements for composite beams.

Even after several years from the original attempts to use channel sections as shear connectors in composite beams there were still not enough research that defines the behaviour of channel shear connectors as accurate as the headed shear connector. (Pashan, 2006) studied the influence of channel height, concrete strength and the dimensions of the channel connector. Results showed that increase in channel length increased the channel shear connector capacity almost linearly. Changes in channel web thickness had a significant impact on failure due to channel fracture. Nevertheless, web thickness did not affect failure by concrete crushing and splitting so much. It was found out that solid concrete slabs had higher load capacities than metal deck slabs because of the highly concentrated loads in relatively small areas in concrete. Based on these results researchers developed two new equations that predicts the ultimate load carrying capacity for both shear connectors embedded in solid slabs and wide ribbed metal decked slabs.

After tests two failure modes were observed;

1. Channel fracture – fracture of the channel web near bottom flange

2. Concrete crushing and splitting

Results showed that monotonic shear strength capacities of specimens were 10 to 23% higher than the reversed cyclic shear strengths. (Shariati, & Arabnejad Khanouki, 2012), (Shariati et al., 2011) have proposed such equations for channel shear connectors embedded in LWAC. (Pashan & Hosain, 2009) have suggested two equations to determine the channel strength embedded in metal and solid slabs. Current research has

been carried out on channel shear connectors to determine their behavior and to make comparisons with other type of connectors (Shariati et al., 2013).

When it comes to conventional push-out tests there are a couple of problems and they have been mentioned briefly. Conventional push-out specimens are prepared with two concrete solid slabs on each flange of a girder so each side of the specimens needs to be cast on different times. This causes two solid concrete slabs with different compressive strengths. Concrete strength is an important factor for ultimate connector capacity. Having two separate concrete slabs with different compressive strengths interrupts the purpose. Also it would cause uneven load and stress distribution. Baran & Topkaya, (2012) introduced a modified push-out specimens and the test assembly as an alternative for conventional push-out tests and applied it for the testing of channel connectors in a study (Baran & Topkaya, 2012). The results showed only one failure mechanism contrary to what other researches shown. All of the specimens were observed to be failed by steel channel web fracture near the fillet. Only one specimen showed weld failure. Test results further reflected that channel height had significant effect on the strength of the channel shear connector and higher channel connectors showed close ultimate load capacities. Concrete strength starts to dominate the strength of connector thus increasing the channel height becomes useless. The output of the experimental study on channel connectors is presented in the form of equations available in various relevant building design standards (Baran & Topkaya, 2012).

2.2. Type of shear connectors

As it is widely known, there are many different types of shear connectors, conventionally they are often categorized as rigid or flexible (Ranković & Drenić, 2002). For rigid connectors, the front side of the connector borne the shear forces and in the proximity of ultimate strength its deformation is insignificant. Rigid connectors

produce heavily concentrated stress on the embedded concrete, which results in concrete failure or the failure of the shear connector welding. Whereas, flexible shear connectors resist the shear forces by shearing, tension or bending at the bottom at a point in the steel beam where plastic deformation happens to connectors once the ultimate load is reached. Flexible shear connectors are more ductile and are not as quick in terms of the manner of failure. Even at high movement between the composite members, the shearing strength is maintained by the shear connectors.

Flexible connectors show a clear indication prior to failure due to sufficient ductility exists in the connection and support their capacity even in the case of higher degree movements in between the two different elements in a composite beam (Ranković & Drenić, 2002). When exposed to real stress condition, in the event of expansion of the load, the connectors behave similarly due to the presence of minor deformation that authorized to assume no movement between concrete and steel in the cross-section. This assumption allows the use of the same approach to calculate the elastic strength of the connector regardless of the kind of connector. This matter is used in a homogeneous assumed cross-section. This approach differs to the estimation of limit strength according to plasticity theory. In that case, slim shear connectors experiencing plastic deformation, are recommended since they allow some definite movement between two materials and consequently a supportive distribution of shear forces takes place. The behaviour of shear connectors matches with the behaviour of steel section in failure.

A complete description, mechanism, manufacturing, functioning, advantages and disadvantages and the expressions for the design of various types of shear connectors such as; headed studs, Perfobond ribs, T-Rib connector, oscillating Perfobond strips, waveform strips, T-Connectors, channel connector, non-welded connectors, pyramidal shear connectors, Hilti shear connector and rectangular-shaped

collar connectors reviewed by Shariati et al., (2012). The most commonly used types of shear connectors used in structural engineering are the headed and Perfobond shear connectors. However, in the last few years, the use of C-shaped connectors has also increased abruptly. In headed stud connectors, the body of the stud and the weld sustain the shear forces and the head resists the tensile force perpendicular to the shear forces at steel-concrete interface. Shear connectors are designed according to two fundamental principles. First, they must resist the horizontal shear forces developed at the interface between two mediums. Second, they should not let the pull up forces separate the two mediums by resisting the tension forces. There are a large variety of mechanical shear connectors, varying in shape, size and methods of attachment (Figure1.5). However, they all have the following similarities;

All mechanical shear connectors are dowels surrounded in concrete. One component is designed to resist the horizontal shear forces and one other component that resists the tensile forces perpendicular to the shear forces hence preventing separation of the two mediums (Oehlers & Bradford, 1995).
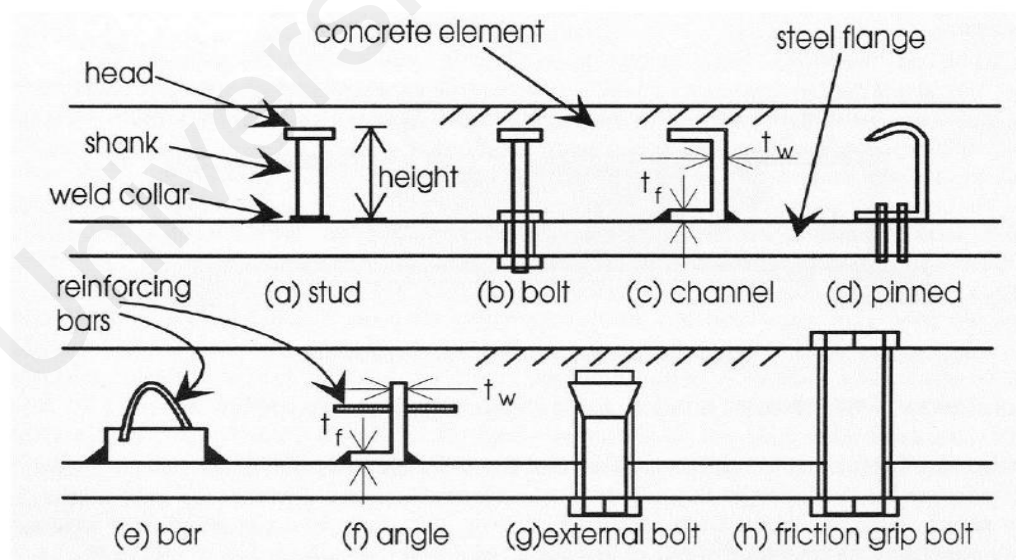
Figure 2.1: Mechanical Shear Connectors (Oehlers & Bradford, 1995)

2.2.1. C-Shaped Channel connectors

Popular use of headed shear connectors comes from their proven performance and easy application process using a welding gun. Even though headed shear studs are popular, their application and installation comes with reliability problems. Unless true care is given to the installation process, welding strength and performance can be affected substantially by the weather, coating material of the steel and surface conditions (Ritchie, 1984). Because of their small load capacity, headed shear connectors installed in relatively huge quantity. Due to these entire drawbacks, researchers and construction companies headed toward the pursuit of other better performing shear connectors. Due to limitations in the use of headed studs and Perfobond shear connectors, C-shaped shear connectors are widely used. These limitations include less resistance under fatigue loading. The welding of these connectors required high welding cost and heavy welding equipment which also requires high amount of electricity to operate (Vianna et al., 2009). These are known as the main problems that come with the headed studs (Chromiak & Studnicka, 2006). Perfobond shear connector needs high skills to pass the steel bars from connector openings. Moreover, the placement of concrete slab at lower reinforcement is also complex (Veríssimo, 2006). This installation of Perfobond connectors also needs high expenses and sufficient time.

One of the advantages of C-shaped connectors is their availability in a variety of hot-rolled steel shapes. Additionally, there is relatively less time and cost required for the installation of C-shaped connectors. The other advantage is high structural capacity and an affordable welding arrangement in terms of labor and cost. The use of C-shaped connectors allows the placement of concrete slab easily at lower reinforcement and also

do not demand additional inspections including bending tests on site. C-shaped shear connectors solve the shortcomings experienced in the use of another type of connectors.

Angle and channel profiles are usually used as C-shaped connectors as shown in Figure1.6. The angle connectors do not have the bottom flange; hence less amount of steel is consumed as compared to channel shear connectors and become more economical. The angle connectors avoid the pull-out of concrete element due to the presence of circular reinforcement in them; however, the problem of passing the reinforcement bars from connector holes requires the same arrangement as adopted for Perfobond shear connectors. Collectively, the C-shaped connectors are a better replacement of other commercially available connectors.
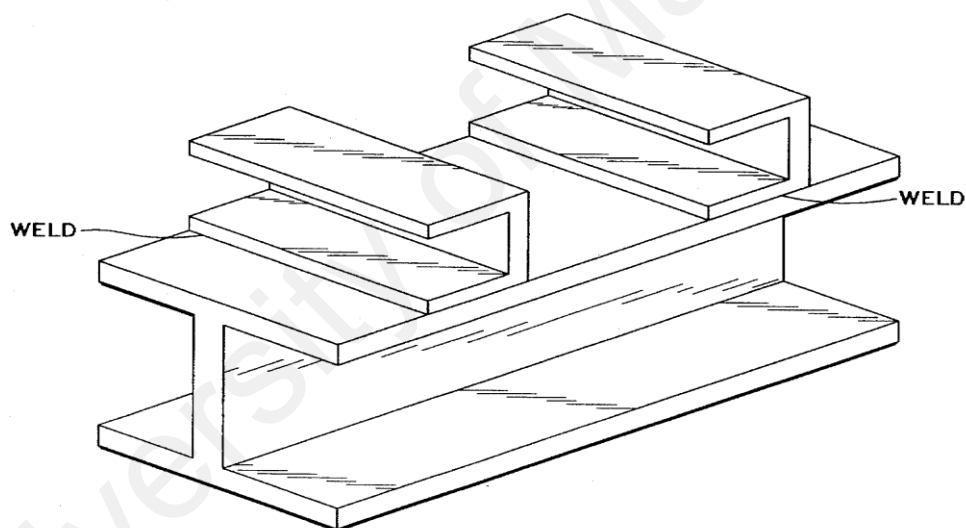
Figure 2.2: C-shaped shear connectors (Veríssimo, 2006)

Channel shear connectors are one of the examined mechanical connectors and in many aspects which are listed below; they are exceeding the headed studs' performance;

- While studs need special installation equipment like welding guns, the conventional welding equipment is enough for channel shear connectors.

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- By contrast, conventional welding has a proven performance and it is more reliable than welding guns.

- Channel shear connector's load carrying capacity is at least 2 times greater than the headed shear studs, in some cases more, and this lead to use fewer shear connectors.

- Fewer shear connectors means lesser working time.

- Channel connectors are stronger and tolerate uneven equipping.

- Using channel connectors with less number creates a safer work environment.

All of these aspects make a good case for channel shear connectors. However, there is not much research done to understand the behavior and the performance of channel shear connectors. The reason for the lack of study may be the popularity of the headed studs. There is already excessive amount of research for headed studs. Furthermore, research on one type connector's behavior mean lots of work and numerical analyses involved and all those cost money. There are a few published researches which takes subject to understand the channel connectors' behaviour by performing push-out and full scale beam tests

2.2.2. Headed Studs

To resist horizontal shear and vertical uplift forces in composite steel-concrete structures, the most commonly used types of shear connector is the head stud, known as the Nelson stud (Figure 2.1). This type of connector contributes to the shear transfer and prevents uplift. It is designed to work with an arc welding electrode, and, simultaneously, after the welding, it then acts as the resisting connector with a suitable head.

Figure 2.3: Headed stud shear connector

Many researches have been carried out on headed stud connectors and various equations have been proposed to estimate the strength of headed studs (Gelfi & Marini, 2002; Lee et al., 2005; Ollgaard et al., 1971; Viest, 1956a). Viest (1956a) carried out the initial studies on headed stud shear connectors, where full-scale push out specimens were tested with various sizes and spacing of the headed studs. The push-out and composite beam tests were used to evaluate the shear capacity of the headed stud. In order to investigate the behavior of headed stud connectors in solid slabs, an accurate nonlinear finite element model were developed by Ellobody (2002), and Lam and Ellobody (2005).

Validations against test results and comparison with data specified in the current codes of practice, such as BS5950 (1994), and AISC (2005), was carried out using the effective numerical model by (Lam & Lobody, 2001). The results of the experiment conducted by these authors are comparable with the results obtained from the finite element analysis. The finite element model offered accurate predictions on the capacity of the shear connection, the load slip behavior of the headed studs and the failure modes.

Ellobody (2002) conducted another finite element model by considering the linear and non-linear behavior of the materials in order to simulate the structural behavior of headed stud connectors. The use of the model in examining variations in concrete strength and headed stud diameter in parametric studies was also presented. Consequently, it was found that the finite element results suggested by BS5950 (1994) may overestimate the headed stud's shear capacity.

The experimental tests to assess the behavior of the shear connection between the steel and lightweight concrete that were carried out at the University of Minho were described in another work by (Valente & Cruz 2004). The behavior of headed stud connectors embedded in ECC (Engineered Cementitious Composites) was investigated by (Li et al., 2006). while, in order to examine the capacity of large headed stud shear connectors embedded in a solid slab, an accurate nonlinear finite element model of the push-out specimen was performed by (Nguyen & Kim 2009).

The AISC (2005), CSA (2001) and Eurocode 4 (2004) standards currently provide design equations for the calculation of the resistance of a headed stud shear connector. The investigation of the headed stud's capacity has been conducted thoroughly and tabulated values can be found in BS 5950: Part 3 (1990) and BS 5400: Part 5 (1983) as well.

The headed stud's root is functioned to transmit the horizontal shear force acting at the steel-concrete interface, while the head is provided for preventing uplift of the slab. The cross-sectional area of a headed stud connector is directly proportional to its shear strength and its ultimate shear strength is influenced largely by the concrete's compressive strength and modulus of elasticity.

2.2.3. Perfobond Ribs

In the late 1980s, Leonhardt et al. (1987) developed a new type of connector called the Perfobond rib. This connector was introduced in recognition of the unsatisfactory behavior of headed studs in which resulting from fatigue problems caused by live loads on composite bridges. Developed in Germany, this connector consists of a welded steel plate, with a number of holes (Figure 2.2) (Lee et al., 2010). The flow of concrete through the rib holes formed dowels that provided resistance in both the vertical and horizontal directions. This shear connector is a viable alternative to the headed stud connector, as signified in the experimental studies conducted previously (Ahn et al., 2010) and recently (Jumaat et al., 2011; Kisa et al., 2011), this connector was initially used in building structures (Ferreira et al., 1998). The fact that not only it ensures the concrete steel bond but also enabled a better anchorage of the internal columns hogging moment has encouraged its adoption. By passing through the Perfobond web holes or simply by being superimposed to the transverse reinforcing bars would allow these bars to be anchored. A study, which had been done by (Zellner, 1987) indicated that a one meter length of Perfobond connector was comparable to eighteen 22 mm diameter's headed studs which were disposed in two lines or twenty four 19 mm diameter's headed studs which were disposed in three lines.

Figure 2.4: Perfobond Ribs shear connector

2.2.4. T-rib connector

In the scope of a study on Perfobond connectors, Vianna et al. (2009) presented an alternative connector for headed studs, called the T-Perfobond (Figure 2.3). The researcher also provided a comparative study between the behavior of these connectors and a limited number of T-Perfobond connectors. By adding a flange to the plate, which acted as a block, the derivation of this connector from the Perfobond connector was created. The need to combine the large strength of a block type connector with some ductility and uplift resistance arising from the holes in the Perfobond connector web was a motivating factor for the development of this T-Perfobond connector.

In order to prevent a premature loss of stiffness in the connection, the T-rib connector detail should minimize the prying action effect (Ferreira, 2000). As leftover rolled sections can be used to produce the T-rib connectors, it can reduce cost and minimize welding work. The four steps involved in the fabrication process of the T-rib connectors are: (i) initial profile, (ii) web holes, (iii) flange holes, (iv) opposite flange saw cut are as shown in Figure 2.3.

For similar longitudinal plate geometries, the resistance and stiffness of T-Perfobond connectors are higher than that of Perfobond connectors. In addition to this

advantage, the use of T-Perfobond connectors offers benefits in terms of saving material and labor, as they are produced by ordinary laminated I or H sections.

Figure 2.5: T-Rib shear connector

2.2.5. T-Connectors

This connector is a section of a standard T-section welded to the H or I section with two fillet welds Figure 2.4. T-connectors evolved from the observation by (Oguejiofor & Hosain, 1997) they stated that a large part of the bearing capacity of a Perfobond strip was the result of the direct bearing of the concrete at the front end of the (discontinuous) Perfobond strip. Therefore, a T section, which has a larger cross section than a single strip, and its shape, was potentially able to prevent vertical separation between the steel-section and the concrete, seemed to be a good alternative.

The behavior of the T-connector is very favorable. The bearing stress on the front of the T is very high, which is a result of the relatively small area. Local concrete crushing occurs, which results in a quasi-plastic performance (Zingoni, 2001). The load capacity for T-connectors are similar to that of the oscillating Perfobond strip, however, the ductility of these connectors is much larger (Rodera, 2008). When theses connectors

are used in concrete with fibers, lightweight concrete or a higher strength concrete, there is a notable increase in the load capacity and ductility of this type of connector. In the case of the T-shape connectors, the strength of the connector itself is vital and the concrete is no longer decisive. Disregarding the Perfobond strip, the resistance characteristic of the T-shape connectors is considered as the highest and its failure mode varies according to different concrete strengths.

Figure 2.6: T shear connector

2.2.6. C-shaped shear connector

Due to the limitations for the use of headed studs and Perfobond shear connectors in composite construction, the use of C-shaped shear connectors may be a recommended alternative, especially in developing countries. Some restrictions on the fatigue behavior of headed studs have been reported such as the commencement of fatigue cracks in welds under cyclic loading, the necessity of specific welding equipment and high power generators on site (Chromiak et al., 2006). Also for the Perfobond shear connector, problems will appear when the steel bars need to cross the

connector openings and it is difficult to position the slab for lower reinforcement (Verissimo et al., 2006).

In addition, the manufacturing of headed studs and Perfobond shear connectors is not as easy as C-shaped shear connectors due to the special shape of the headed studs and the need of making holes in Perfobond shear connectors, which is a time consuming and an expensive procedure.

There are commercially available standard sized hot rolled steel profiles of C-shaped shear connectors mostly in the steel industry. It is also easy to prepare these types of connectors by simply cutting their plain steel profiles. One may also notice that manufacturing cost and time to manufacture C-shaped connectors are significantly lower compared to the headed stud and Perfobond connectors.

Also, the C-shaped connectors have high load carrying capacity and can be welded to steel beam by using the conventional reliable welding system. Some inspections, like bending test which is needed for headed stud connectors, are not necessary for these types of shear connectors and also positioning the slab for bottom reinforcement, may not be a challenge when C-shaped shear connectors are employed (Ciutina & Stratan, 2008). Generally speaking, C-shaped shear connectors are preferred as they overcome the constraints and difficulties of using the headed studs and Perfobond shear connectors in composite beams.

The C-shaped shear connectors can be made with both angle and channel profiles as shown in Figures. 2.5 to 2.7 The angular profiles can also include L-shaped shear connectors in addition to the C-shaped one as well. Since angle connectors in the absence of bottom flange in comparison to channels, they could be cheaper and more economical than channel connectors. A hoop reinforcement should be provided for L-shaped angle connector to prevent uplift of concrete in the composite system (Eurocode 4, 2004), a similar problem also occurs in the case of Perfobond connectors when the

steel bars need to cross the connector openings. Therefore, it is better to use the C-shaped angle shear connector than the L-shaped connector in composite beams.

Figure 2.7: Typical angle shear connector

Although channel shear connectors, as one of the popular C-shaped shear connectors, are used more in structures because of their accepted well-behaved performance. Angle shear connectors without bottom flange could be cheaper and more economical than channel shear connectors by saving more steel material in composite beams. The convenient welding process of angle connectors compared to channel connectors is a further advantage.

Figure 2.8: Typical channel shear connector
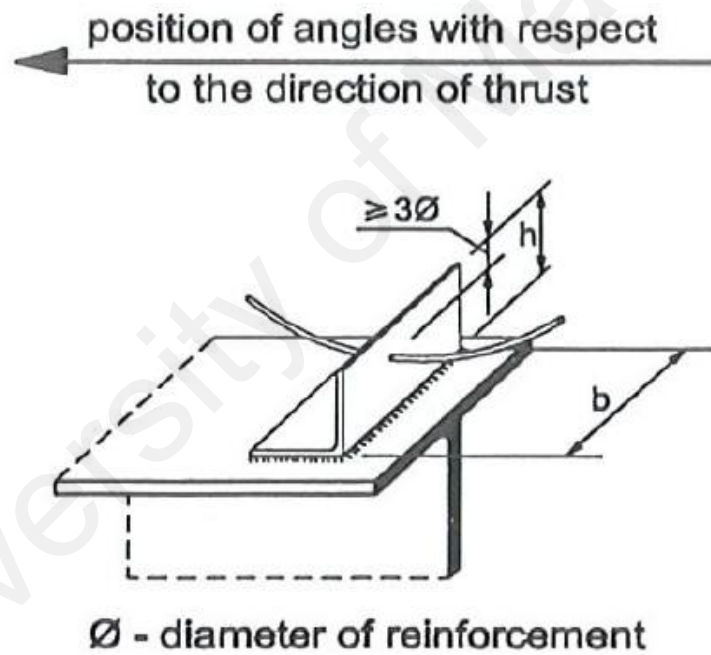
Figure 2.9: Typical L-shaped angle shear connector (Eurocode 4; CEN 2001)

2.3. Experimental testing of shear connectors

A typical push-out type tests are usually used to evaluate the load-slip behaviour of shear connectors. To date, a great deal of research has been conducted on push-out tests also called composite beam tests. In general, to conduct push-out tests, specimens

are placed on a universal testing machine on two bearing pads to eliminate the uneven geometry and minimize its effects. Shear load is applied gradually using the machine with increments that are approximately 10 percent of the expected specimen capacity. During the test, amount of slip versus applied load is recorded. According to (Eurocode 4, 2005), the push-out sample comprises on a steel beam placed vertically and supported by two same concrete slabs. Beside the specimen geometry, (Eurocode 4, 2005) also defines the test procedure. The initial phase of the test is characterized by 25 cycles of loading and unloading, between load values of 5% and 40% of the predicted ultimate load. Following this, the test is controlled by deformation, with measurements of slip at a persistent rate. Lateral displacement between slabs is also measured. The test proceeds until failure; however, the slip is noted at different intervals prior to the point when 80% of the ultimate load is achieved.

The slip capacity measured in a push-out specimen should be considered as the maximum slip corresponding to the characteristic load. The characteristic load is taken as the smaller failure load divided by the number of shear connectors and reduced of 10%. The characteristic slip capacity is considered equal to 0.9 ultimate slip. A mathematical analysis is then performed to propose an empirical formula in order to evaluate the structural capacity of the particular connection which is tested in the experiment. Generally results will show similarity to Figure 2.8. These tests are usually run monotonically; the Figure also shows the unloading behaviour after significant slip has occurred in case of a major overload event (Viest et al., 1997).
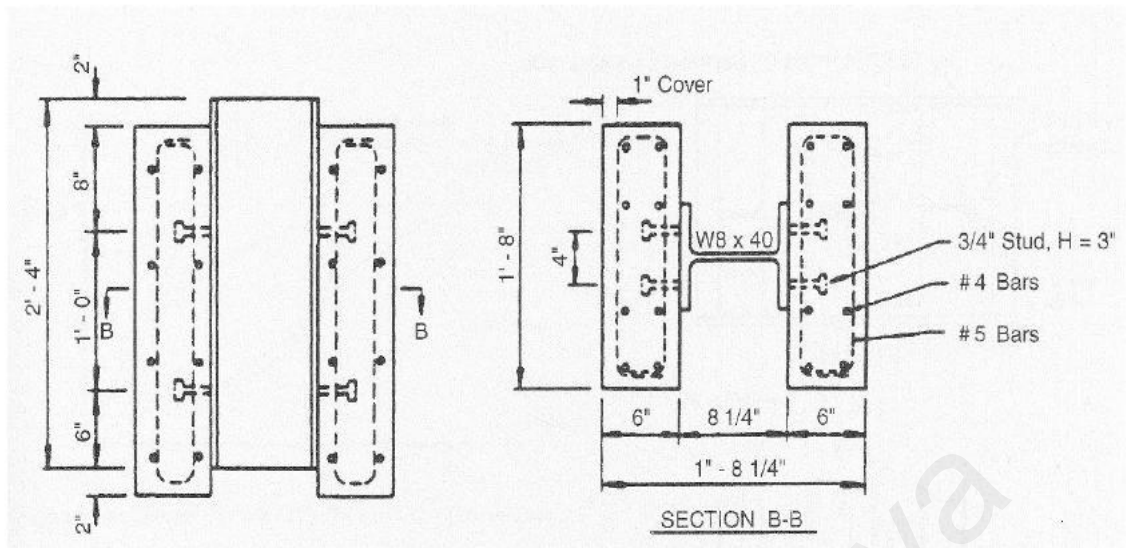
Figure 2.10: Typical Push-Out Test Specimens (Viest et al., 1997)
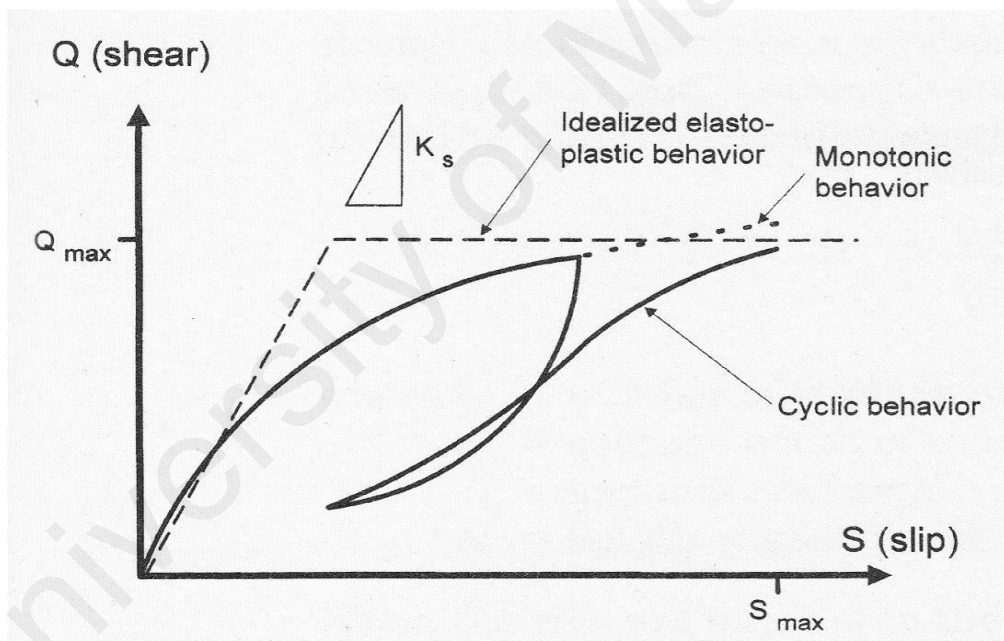
Figure 2.11: Typical Push-Out Test Result (Viest et al., 1997)

For strength evaluation of a composite beam, the individual strength characteristics of each shear connectors and the amount of shear force at a particular distance for which the connectors are designed should essentially be known. Typically, the strength of shear connectors can be assessed by considering a number of factors, including their shape and dimension, the quality of forming material, the compressive

strength of concrete, nature of applied load, method of connecting the steel element, effective length between the two connectors, concrete slab size, and the amount and method of placing the reinforcing rods. Consequently, the individual experimental investigation or numerical modelling for each type of shear connector in order to obtain an accurate estimation of the behavior of shear connectors is required.

While discussing the behavior of shear connectors, most of the researchers have emphasized only on the strength of these connectors and rare information is discussed to utilize the load-slip relationship to evaluate the stiffness of shear connectors. A typical load-slip curve is shown in Figure 2.9. Knowledge about the stiffness of shear connectors is essential to use the equation of the partial interaction theory of composite steel-concrete beams. Johnson and Molestra (1991) defined the shear connector stiffness as the secant stiffness at half the shear connector ultimate load. Yam and Chapman (1968) conducted a study on the inelastic behavior of simply supported composite beams, based on Newmark's model. Although there are several mathematical expressions describing the shear connector load-slip curves, the studies indicated that it was slightly challenging to discover a common regression formulation for the shear connector stiffness because of the magnitude of scatter in this value when plotted against other parameters.

Several alternative methods have been generated by researchers to solve this problem. Researchers have been using a couple of different test methods, but results typically consist of load versus slip relationship and failure mode. However, the push-out testing is more convenient and economic than the composite beam test and it has been verified to be able to provide the relevant properties for shear connectors with acceptable accuracy although there is some difference of stress state between the push-out specimen and beam.

2.4. Influence of concrete surrounding shear connectors

Floor systems based on non-composite interaction between steel and concrete elements were often used in the construction of bridges before the 1970s. However, the current load requirements could not be fulfilled through the construction of bridges with such a system, thus, requiring many existing bridges to be replaced or strengthened. Connecting two different elements in an efficient way is a potentially economic way to strengthen these floor systems as it allows for composite action to be developed. In non-composite structures, both steel and concrete act separately in flexure. Hence, by using shear connectors, the two structural components and strength of the girders could be increased by up to 50% (Kwon et al., 2010). By connecting the steel element to the existing concrete part, an efficient transfer of shear forces at the interface of elements enables the benefits of composite actions to be achieved. The modern construction bridges uses pre-weld shear connectors before the casting of concrete slab (Kwon, 2009).

To improve the performance of all types of shear connectors, High Strength Concrete (HSC) is highly recommended by a number of researchers, (Bullo & Di Marco, 2004) however, only one study provides some guidance to estimate the structural performance of channel connectors when confined by HSC. The present study investigates the performance and structural behaviour of channel connectors with varying profile and embedded in variable strength levels of HSC under both static and cyclic loading. Comparisons of test results with the design approaches suggested by different codes are also highlighted.

Lightweight Aggregate Concrete (LWAC) in the composite section is also widely accepted application of concrete type particularly in United States and Europe. This type of concrete saves almost 10–20% cost as compared to normal weight concrete

with a relatively low density that permits the use of lower size structural elements. The composite beam using channel shear connector has to be checked for the application in lightweight aggregate concrete (LWC) which specially composite bridges represent a further interesting field of this system in it because of its considerable lower modulus of elasticity (King et al., 1965; Valente & Cruz, 2009). Reasonable results for using LWC in composite structures were obtained by some researchers (Slutter & Driscoll, 1963) (Buttry, 1965; Chinn & Zimmerman, 1965) (Cas et al., 2004; Fisher, 1971; Galjaard & Walraven, 2000; Shariati et al., 2011; Steinberg, 1973; Valente & Cruz, 2004; Valente & Cruz, 2009).

2.5. Artificial Intelligence Approach

2.5.1 General

Artificial neural networks (ANNs) are computational models prepared by human's nervous system, particularly the brain, and are being utilized in machine and construction industries for a long time. Natural neurons get directions by using synapses situated at the membrane of the neuron. If the signals received by the neurons are powerful enough, the neuron is triggered and releases a signal through the axon. The released signal is then passed to other synapse that trigger the other neurons (Heylighen & Gershenson, 2003). Figure 2.10 shows a natural neuron.

ANN models have the capability to understand the appliance mechanism along with pattern recognition. ANNs are modelled as a scheme of unified neurons able to calculate the values assigned them during input.

For example, in order to recognize handwriting, some neurons are compiled and feed as an input in the system, the ANN activates by reading the pixels of input. The readings are checked and converted by a function (selected by the network designer) and then transferred to other neurons. This process continues to be repeated until an

output set of neurons is activated. This represents the character which is read by the neurons. Similar to other systems those work on the basis of an input data, ANNs are capable of solving an extensive range and type of problems that are difficult to solve through ordinary principle-based program structures including computer software.
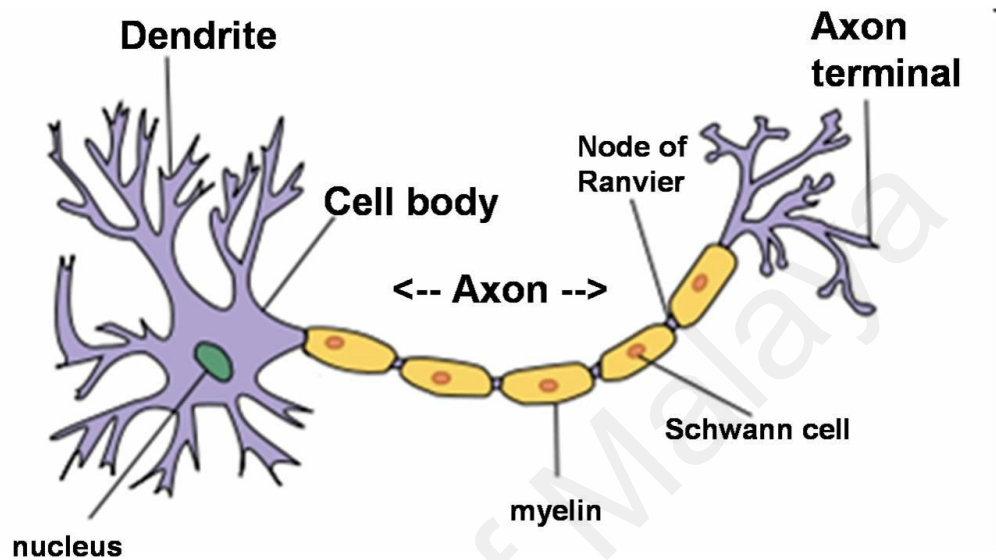
Figure 2.12: Natural Neurons (Heylighen & Gershenson, 2003)

The intricacy of actual neurons is greatly distracted during the modelling of artificial neurons. The process of artificial neurons modelling follows then multiplication of input with the strength of the received signals and the computation of mathematical function to evaluate the initiation of the neuron. An additional function calculates the output of the artificial neuron (sometimes independent on a certain threshold). ANN syndicates non-natural neurons to process data (Heylighen & Gershenson, 2003).

ANNs have many more advantages as compared to the traditional numerical computing methods. The immensely equivalent processing, circulated storage of data, little sensitivity to mistake, a sufficiently robust procedure after training, simplification and flexibility to novel data are some of the major advantages of (Waszczyszyn, 1998).

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ANNs are comprised of five key parts including inputs, weights, sum function, activation function and outputs. Inputs are the data that move in the cell through former cells present in the outside system. Weight is the value to represent the influence of input in the preceding layer on process element. Sum function computes the influence of input and weight completely on this process element. This function computes the remaining input that move toward a cell (Topcu & Sarıdemir, 2008).

The data is spread by neural network in same direction layer by layer. In addition to the input and output layers, intermediate layers, known as 'hidden layers', of neurons also exist. Figure 2.11 illustrates the arrangement of a typical neural network.
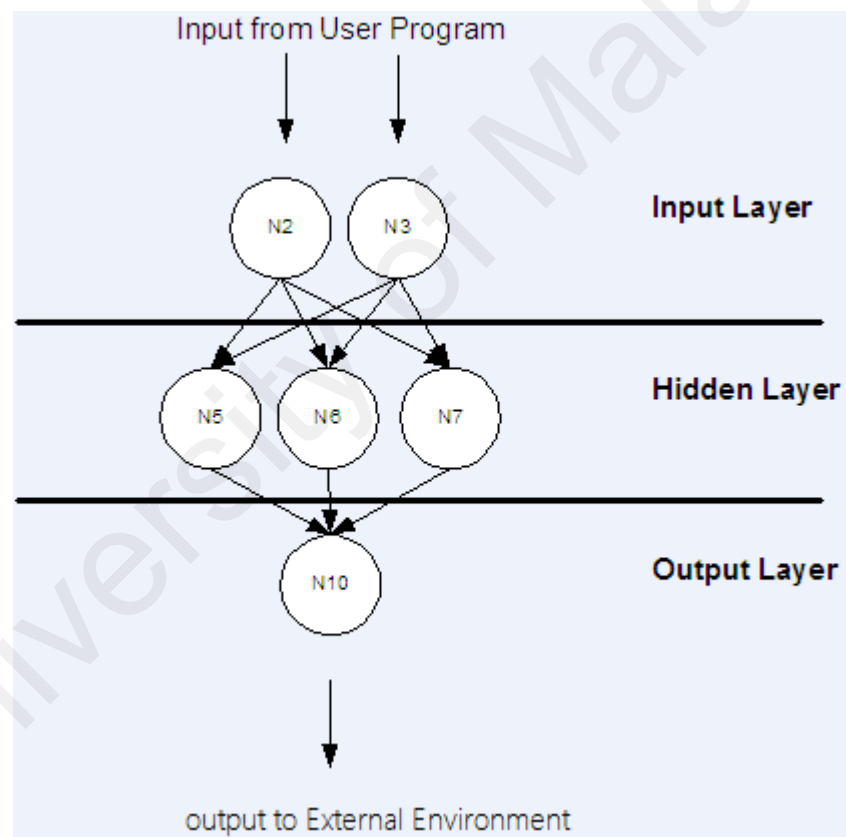
Figure 2.13: Typical Neural Network (Riesenhuber & Poggio, 1999)

Nowadays, biophysical and neuromorphic simulations are performed by newly invented computational devices in CMOS which include a provision of introducing Nano devices for full scale major components analyses and complication. On a

successful completion of proposed provision, neural computation will step forward to a destination beyond digital computation, because it depends on learning rather than programming and because it is fundamentally analog rather than digital even though the first instantiations may in fact be with CMOS digital devices.

During the last few years, the work of Jürgen Schmidhuber at the Swiss AI Lab IDSIA in formulating a high class recurrent neural networks and deep feed forward neural networks has been recognized widely. Alternatives of the back-propagation algorithm and unverified methods are also able to be used to teach profound, extremely nonlinear neural architectures like the 1980 Neocognitron (Fukushima, 1980) and the "standard architecture of vision by (Riesenhuber & Poggio, 1999).

Artificial intelligence (AI) as a glimpse of human intelligence is shown by machines. Nowadays, it has been recognized as a field of academic studies. These days the approach of AI is being taught in academic and commercial institutions. Major definitions of AI declares it as the knowledge of intelligent agents (Poole et al., 1998), whereas the term intelligent agent reflects a protocol that observes its atmosphere and perform activities that enhances its probabilities of achievement. John McCarthy (McCarthy & Hayes, 1968), consider AI as the knowledge of inventing intellectual machines.

The study of AI is significantly technical and specific, and is intensely divided into subfields that are not usually interconnected. One part of a subfield focusses on societal issues and other subfields focus on technical and scientific issues. AI research has another type of classification based on the solutions. A few subfields find out the solution of specific problems and other subfields option for any possible approach or some specific procedure which may help to achieve the required application.

The purpose of AI study is to get help from perception, information, development, wisdom, communication, awareness and the capability to transfer and

operate entities. Recently computational intelligence, conventional symbolic AI and the use of statistical techniques are the major utilization of AI approach, (Kurzweil, 2005), however AI approaches are still looking for a General or Strong intelligence (Poole et al., 1998). The tools majorly utilized in AI are the forms of exploration and mathematical optimization, systemic approaches following economics and probability rules and logic. The AI approach covers a lot of fields including construction, computer science, biology, psychology, linguistics and languages, and neurosciences.

2.5.2.   Why use Artificial Intelligence (AI) system approaches

Numerous engineering applications such as nuclear energy (Lali & Setayeshi, 2011), concrete technology (Hakim, 2011), stability of structures (Flood & Kartam, 1994) and soil science (Yilmaz & Kaynar, 2011) have successfully applied the Artificial Intelligence (AI) system approaches for modelling purposes. This includes the Artificial Neural Network (ANN), Fuzzy Inference Systems (FIS), and neuro-fuzzy/ fuzzy-neural systems among others.

The Fuzzy logic systems make a more precise alternative to model the association among the most complex environmental variables. This technique produces an accurate decision-making process through the use of mathematical relationships and qualitative variables. First introduced by (Zadeh, 1968), Fuzzy logic works on a self-oriented mathematical computation to convert the problem variables into a programmed assessment that needs expertise to provide the desired solution.

When ANNs are combined with Fuzzy Inference System (FIS), the Fuzzy neural systems are produced which are normally used to create powerful tools for computing. The properties (fuzzy rules and fuzzy membership functions) of data samples in the learning of a fuzzy inference system are determined by ANFIS through the use of the ANN theory. In this research, for the purpose of modelling the structural performance

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of channel connectors, ANFIS model based on Takagi-Sugeno theory is used (Wang et al., 1995).

FIS is applied using a feed-forward network and a hybrid learning method. This includes the recursive least square (RLS) method, back propagation theory from ANNs and clustering techniques which are combined to properly develop FIS based on the available data. Concisely, the ANFIS combines ANNs and Fuzzy logic. The ANFIS uses the statistical characteristics of ANNs in tuning rule depending on FIS which approaches the method of human brain to process information. In modelling nonlinear systems, the use of ANFIS has proved to be reliable due to the ability to understand different aspects of the set of information and adjust the arrangement features in accordance with a particular error eliminating criteria. Moreover, by recalling the earlier set of data, ANFIS maps unobserved inputs into the corresponding outputs. The use of ANFIS and ANN models have been applied by (Bilgehan, 2011) to analyse the buckling phenomenon of prismatic columns under axial load. Through this study, Bilgehan concluded that as oppose to the multilayer feed forward ANN learning by back propagation algorithm, the ANFIS architecture with Gaussian membership functions performed better.

ANFIS was introduced by (Jang, 1993). It is a neuro-fuzzy system (NFS) which follows the implementation of a fuzzy method into the context of neural networks. The relationship between input and output is developed by a combined mapping of human brain with a generated input-output data based on a hybrid algorithm comprises of the gradient descent and least squares estimates (Jang, 1993; Mashrei, 2010).

ANFIS is considered as a vital tool to solve complex civil engineering problems (Akbulut et al., 2004; Cüneyt Aydin et al., 2006; Fonseca et al., 2008; Tesfamariam & Najjaran, 2007). For civil engineering applications, the experimental data is mapped with a set of variables in input space to a set of response variables in output space

through a mathematical model. It should be noted that the traditionally modelling of underlying schemes may provide complex and inflexible solution. In order to overcome this issue, a novel modelling technique is introduced in the rulebook of soft computing with neural network and fuzzy logic. A good sign is that the major requirement of these novel models is available for the civil engineering problems that are a set of information or data.

In this study, architecture for modelling complex systems in function approximation and regression based on the ANFIS was applied for selection of the most influential shear strength parameters of channel shear connectors. The shear strength was based on 4 parameters as input of ANFIS. To better analyse shear strength, it is desirable to select a subset of shear strength parameters through the variable selection procedure using ANN (Akbulut et al., 2004; Cüneyt Aydin et al., 2006; Fonseca et al., 2008; Tesfamariam & Najjaran, 2007). ANNs can be defined as an architecture comprising massively parallel adaptive processing elements interconnected via structured networks. Thus, the neural network models generated from this data must therefore rely on how effectively the chosen sensor data represents the system. Therefore, in order to build a model that can predict a specific process output, it is desirable to select a subset of variables that are truly relevant to this output. A solution to the variable selection problem could be the utilization of prior knowledge in order to screen out the irrelevant variables. In this investigation, the ANFIS was used for the variable selection.

It should be noted that till date, there is no study available in literature into the channel shear connectors using ANFIS and AI techniques. The present study will help to evaluate the accurate performance of channel connectors in composite construction and will open new doors for the researchers.

2.5.3. System modelling

Figure 2.12 illustrates a schematic of the system modelling problem utilizing ANFIS. As can be seen from this Figure, the actual system is accurately simulated by using the appropriate learning techniques in order to tune the parameters of the estimated intelligent system. In brief, performance function, normally the mean squared error (MSE) between the output of the intelligent system and the actual response is minimized.
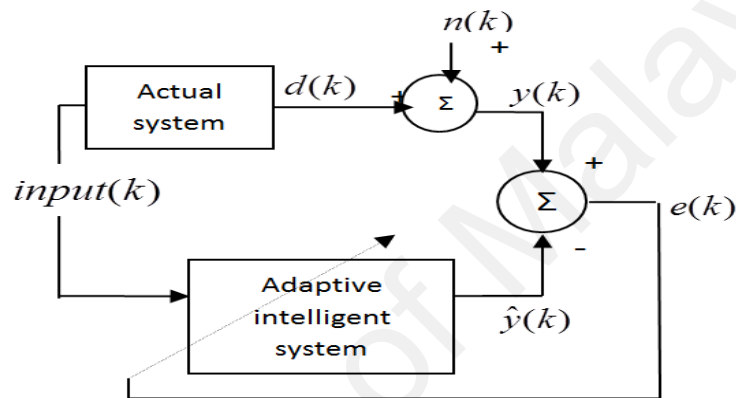
Figure 2.14: System modelling using an adaptive intelligent system (Jang, 1993)

The objective function in system modelling problems is expressed as follows:

$$MSE = \frac{1}{L}\sum_{k=1}^{L}(\hat{y}(k) - y(k))^2 \qquad \text{(Eq. 2.1)}$$

Where $y(k)$ is the noisy output of the actual system (measured or observed output), $\hat{y}(k)$ is the adaptive intelligent system output and L is the number of instances. Some cases are noise free where $y(k)$ is equal to $d(k)$ which is the desired output. When noise is present, $\hat{y}(k)$ is the estimation of the desired output or the semi desired output.

2.5.4. Fuzzy Expert System

It is a universal behaviour that common sense is used to solve the complex problems in daily life. However, the approaches of common sense may vary from expert to expert and person to person based on their relative knowledge about the background of the problem and possible solution of the complex matters. For example, a Civil engineer may face difficulty to repair a computer or even one without the knowledge of computer cannot understand the conversation between two experts discussing the problem encountered in computer and its possible solution. There is a question that is it possible to simulate the unclear and ambiguous conversation of two computer experts in order to make it beneficial for the person who does not have sufficient knowledge about the repair of the computer. Fuzzy logic is a philosophy of fuzzy sets used to improve imprecision. This philosophy assumes that there is a certain degree of limit of all things exist in this system for example, temperature, height, speed, distance, beauty all come on a sliding scale. This theory interprets the thinking of people. It can simulate our decision power, knowledge and interest in some specific field and one's common sense. This reflects a proper and idealized simulation of human intelligence.

Uncertainties and vague concepts can be processed appropriately by human reasoning. Fuzzy logic theory models the doubts and the thoughts, logics and point of view and concepts of human mind (Abraham, 2005). According to the Boolean logic, only two concepts, True or False, are usually used and reflected respectively by the digits 1 and 0. However, in Fuzzy logic, the classical theory of binary membership in a set is extended to incorporate memberships between 0 and 1 and hence allows intermediate values between these two values. Therefore, each proposition can be either True or False to a certain degree between them. A classical set A, $A \subseteq X$, with X as the

space of objects and x as an element of X, is defined as a collection of elements $x \in X, x \in X$ such that x can either belong or not belong to the set A. Eq. 2.2 below describes the set A

$$A = \{x | x \in X\},$$ (Eq. 2.2)

whereas, a fuzzy set A in X is defined by Eq. 3.3.

$$A = \{(x, \mu_A(x)) | x \in X\},$$ (Eq.2.3)

Where $\mu_A(x) \mu A(x)$ is the membership function for the fuzzy set A. Here, A is a linguistic term (label) that is determined by the fuzzy set. The membership function maps each element of X to a membership grade between zero and one $(\mu_A(x) \in [0,1])$. For example, this set can present X as 'Medium', which is a linguistic term that can be described by a fuzzy set with soft boundaries. Figure 2.13 illustrates two sets, which are based on the Boolean logic and the fuzzy logic respectively.

(a)   (b)
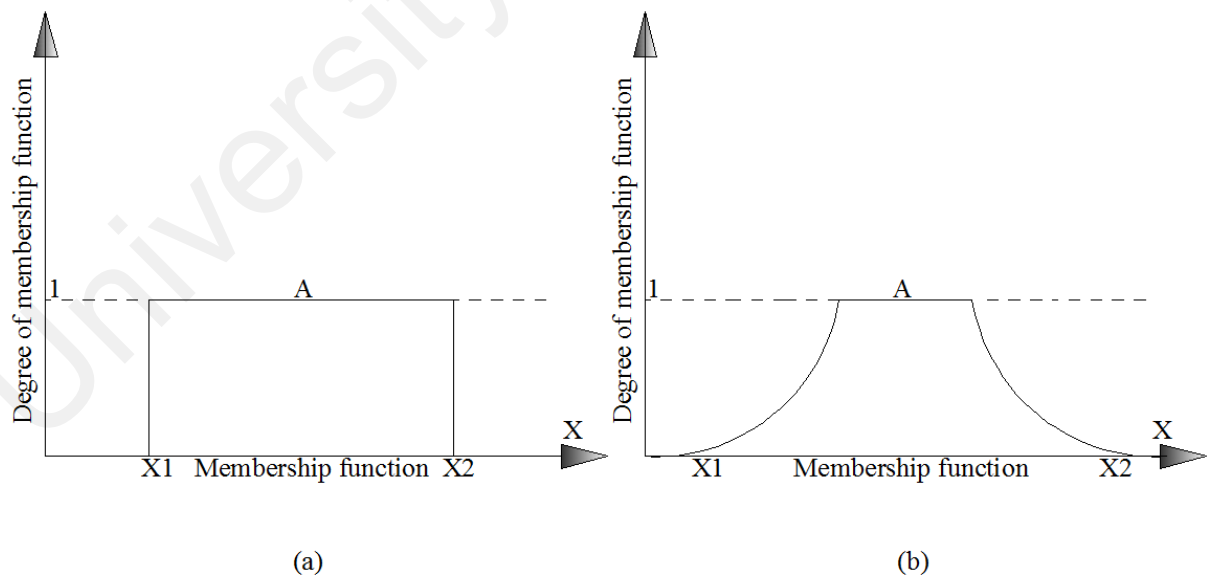
Figure 2.15: An example of: (a) Classical Boolean set, and (b) Fuzzy Logic set (Jang, 1993)

2.5.5. Fuzzy Inference System (FIS)

Fuzzy systems simulate the expertise and knowledge of human being about the problem in a mode of fuzzy rules, IF–THEN rule, (also termed as antecedent and consequent rule). This is the benchmark to utilize and simulate human's knowledge in fuzzy logic philosophy. Eq 3.4 shows the main structure of the fuzzy rule:

IF <antecedent> $THEN$ <consequent>   (Eq. 2.4)

The antecedent of a fuzzy rule can conditionally be satisfied to a degree. Using AND, OR and NOT logic operators, the antecedent of a fuzzy rule may combine multiple simple conditions into a complex string, similarly to that of conventional rules. The outcome of a fuzzy rule can be classified into two main categories:

a) Fuzzy consequent   (Eq.2.5)

where C is a fuzzy set.

b) Functional consequent   (Eq.2.6)

where p, q and r are constant.

$IF \ x \ is \ A \ and \ y \ is \ B \ THEN \ f \ is \ C$

(Eq.2.7)

$IF \ x \ is \ A \ and \ y \ is \ B \ THEN \ f = px + qy + r$,   (Eq. 2.8)

FIS consists of four pillars as shown in Figure 2.14. A FIS comprises of a 'fuzzifier' which, through membership functions that represent fuzzy sets of input vectors, transforms the 'crisp' inputs into fuzzy inputs. Besides, it contains knowledge-base which includes the information given by the expert in the form of linguistic fuzzy

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rules. An inference-system (Engine) uses them together through a reasoning method and a 'defuzzifier' through which the fuzzy results of the inference was transformed into a crisp output using a 'defuzzification' method (Herrera & Lozano, 2003).
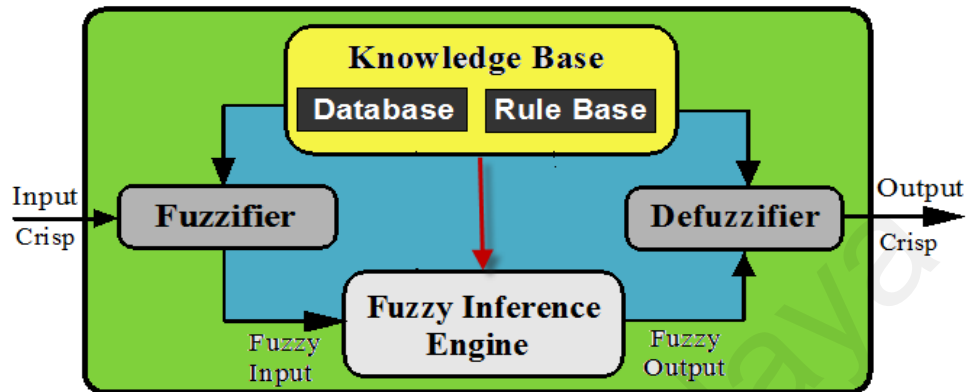
Figure 2.16: Flow diagram of a fuzzy inference system (FIS) (Mamdani & Assilian, 1975)

A further explanation of the process can be understood clearly by following points:

1. FUZZIFICATION based on a definition of the membership functions as an input which defines the actual data set in order to estimate the accuracy of statement for every individual rule evidence.

2. INFERENCE computes the truth value of each rule evidence and provides a conclusion of every individual rule. This phenomenon assigns a unique fuzzy subset to each output variable for each rule. MIN or PRODUCT are the only terms considered as inference rules. MIN inferencing considers that the output membership function is clipped off at a height corresponding to the rule premise's computed degree of truth (fuzzy logic AND). In PRODUCT inferencing, the output membership function is scaled by the rule premise's computed degree of truth.

3. COMPOSITION, as the title is self-explanatory, gathers all individually assigned fuzzy subsets to each output variable in order to constitute an identical fuzzy subset.

The terms, MAX or SUM are used to operate. To perform MAX type of composition, the combined output fuzzy subset is developed by considering the point to point highest overall value of fuzzy subset which was designated to each variable by FIS. To perform SUM type of composition, the combined output fuzzy subset is constructed by taking the point wise sum over all of the fuzzy subsets assigned to the output variable by the inference rule.

4. DEFUZZIFICATION may be an optional step to perform. This is applied when a crisp number is desired to express the fuzzy output set. Defuzzification function may be further classified into CENTROID and MAXIMUM methods. CENTROID method based on the operation that the crisp number used to define output variable value variable is calculated by evaluating the centre of gravity variable value of the membership function equivalent to the fuzzy value. To apply MAXIMUM method, the maximum obtained truth value of fuzzy subset is considered as the crisp number value.

The knowledge-base theory is based on two parameters. One is the membership functions of the fuzzy sets used in the fuzzy rules which are known as data-base, and a collection of linguistic rules that are combined by a specific operator which is known as rule-base. Figure 2.14 illustrates the generic structure of a FIS. The two common types of FIS differ in accordance with the differences between the specifications of the consequent part of fuzzy rules. In the first fuzzy system, the inference method proposed by Mamdani (Mamdani & Assilian, 1975) was used in which fuzzy sets defined the rule consequent.

Takagi-Sugeno-Kang (TSK) fuzzy structures proposed the second fuzzy system which contains an inference engine where, instead of a fuzzy set, a weighted linear combination of the crisp inputs was used for the conclusion of a fuzzy rule (Mamdani & Assilian, 1975). Eq. 3.6 presents the structure of the TSK system. For the purpose of approximating large nonlinear systems, the use of the TSK models is

suitable.

The knowledge-base approach consisting of the database and rule-base of a FIS can be developed in accordance with an expert's knowledge by selecting the membership functions and rules. This enables fuzzy models to help in extracting expert knowledge at an appropriate level. Since the fuzzy systems can also be constructed from data, the problem of knowledge acquisition can be alleviated. In order to analyze the data with the best possible accuracy, a variety of techniques have been used. With the use of available data, there are two common approaches for constructing a FIS. In the first approach, the rules of the fuzzy system are often designated a priori and during the learning process, the parameters of the membership functions are adapted from input to output data using an evolutionary algorithm (e.g. genetic algorithm). Meanwhile, the second approach is where the fuzzy system can be generated using hybrid neural nets that define the shape of the membership functions of the premises. This learning procedure and architecture is being referred to as an adaptive network-based fuzzy inference system (Jang, 1993).

2.5.6. Adaptive network-based fuzzy inference system (ANFIS)

A multilayer feed-forward network based on assigning a particular task to each node on incoming signals and a set of parameters pertaining to this node is called the ANFIS (Jang, 1993). Utilizing the available data set for both input and output values, a FIS can be generated by ANFIS provided that membership function parameters are tuned (adjusted) using either a back propagation algorithm alone, or in combination with a least squares type of method. ANFIS has the same capability as ANN to provide output of unobserved inputs by recalling the earlier provided inputs. Figure 2.14 illustrates a simple structure of this type of network having just two inputs of x and y and one output of Fis.
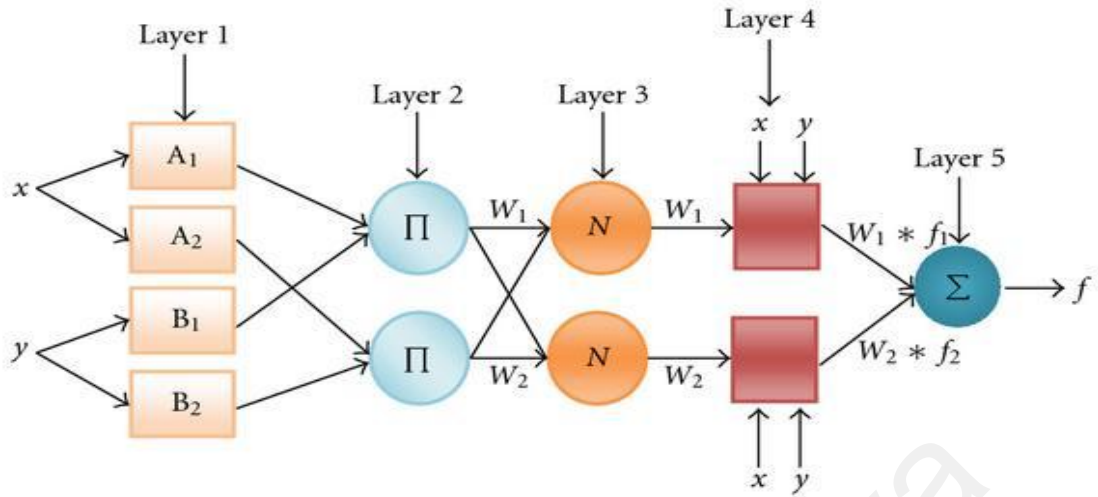
Figure 2.17: ANFIS architecture (Jang, 1993)

ANFIS contains five layers in its architecture which include the fuzzify layer, product layer, normalized layer, defuzzifier layer, and total output layer, as shown in Figure 2.15.

It is emphasized here that the general form of a first-order TSK type of fuzzy if–then rule has been given by Eq 2.9 by assuming just two membership functions for each of the input data x and y. Here the rule i of the ANFIS is re-written as:

Rule i: *IF x is A_i and y is B_i THEN $f_i = p_i x + q_i y + r_i$*, $i = 1,2,...,n$ (Eq. 2.9)

Where n is the number of rules and p_i, q_i and r_i are the parameters determined during the training process. At the first stage of the learning process, the membership function (μ) of each of the linguistic labels A_i and B_i are calculated as follow:

$O_{i1} = \mu_{Ai}(x)$, i=1,2,…,n (Eq.3.10)

$O_{i1} = \mu_{Bi}(y)$,i=1,2,…,n (Eq. 2.11)

At the second layer which is the product layer, the previously calculated membership degrees of linguistic variables are multiplied as shown in Eq. 3.12.

$O_{i2} = w_i = \mu_{Ai}(x) \, \mu_{Bi}(y)$, i=1,2,…,n (Eq. 2.12)

The third layer, the normalized layer, where the ratio of each weight to the total weights is calculated:

$$O_{i3} = \sum \overline{w_i} = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad i=1,2,\ldots,n \qquad \text{(Eq. 2.13)}$$

The fourth layer is the defuzzification layer with adaptive nodes where their outputs depend on the parameter(s) pertaining to these nodes and the learning rule specifies how these parameters are altered to minimize the measure of prescribed error (Jang, 1993). The relationship for these nodes is as follows:

$$O_{i4} = \sum \overline{w_i}\, f_i = \sum \overline{w_i}(p_i x + q_i y + r_i) \qquad i=1,2,\ldots,n \qquad \text{(Eq. 2.14)}$$

Finally, in the fifth layer, the summation of all the incoming signals is performed where the output of the system is the final result:

$$O_{i5} = \sum_{i=1}^{n} \overline{w_l}\, f_i \qquad i = 1,2,\ldots,n \qquad \text{(Eq. 2.15)}$$

CHAPTER 3. RESEARCH METHODOLOGY

3.1. General

The methodology of this research can be divided to two main parts. Experimental and parametric study; In the experimental work, sixteen push out test using channel shear connectors embedded in High Strength Concrete (HSC) was tested under monotonic loading in two different types of HSC. The push out test specimens comprise of eight different samples with different geometries and each specimen was tested twice to obtain better accuracy of the results. The flow chart of the methodology can be shown in the summary in Figure 3.1

3.2. Experimental test program

Eight push-out specimens divided into two series based on the concrete strength and the size of channel shear connector in the concrete slabs were made. All the eight samples have been tested twice for accurate results. All the details of push-out specimens followed those sizes suggested by research of Maleki et al (Maleki & Bagheri, 2008a; Maleki & Mahoutian, 2009). Four types of channels – 100 and 75 mm in height and 30 and 50 mm in length – were used. The 100 mm high channels had a flange thickness of 6 mm and web thickness of 8.5 mm while the 75 mm channels had a flange thickness of 5 mm and a web thickness of 7.5 mm.

Based on the strength of concrete and the size of channel shear connector in the concrete slabs, push-out specimens which consist of a steel I beam with two slabs attached to each flange of the beam were prepared. To each beam flange, one channel was welded and for all slabs, two layers of steel bars with four 10 mm diameter steel bar

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hoops were applied in two perpendicular directions. Figure 3.2 illustrates the details of a typical specimen.
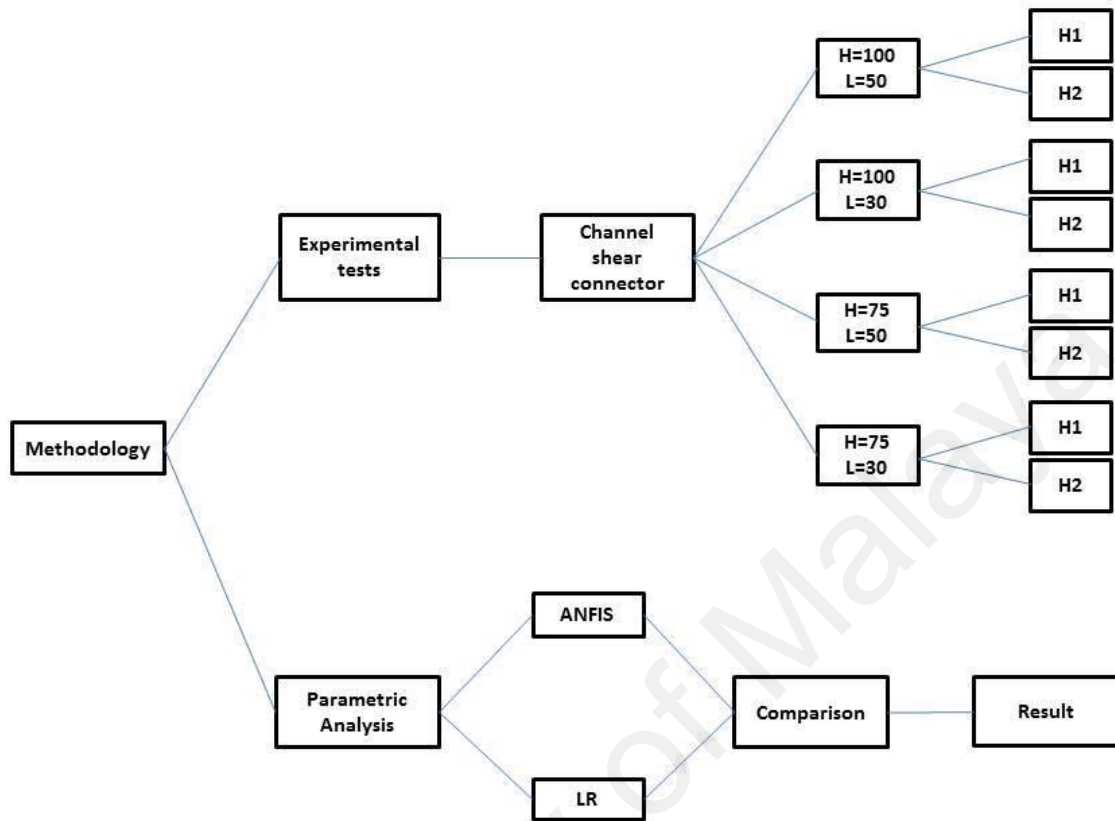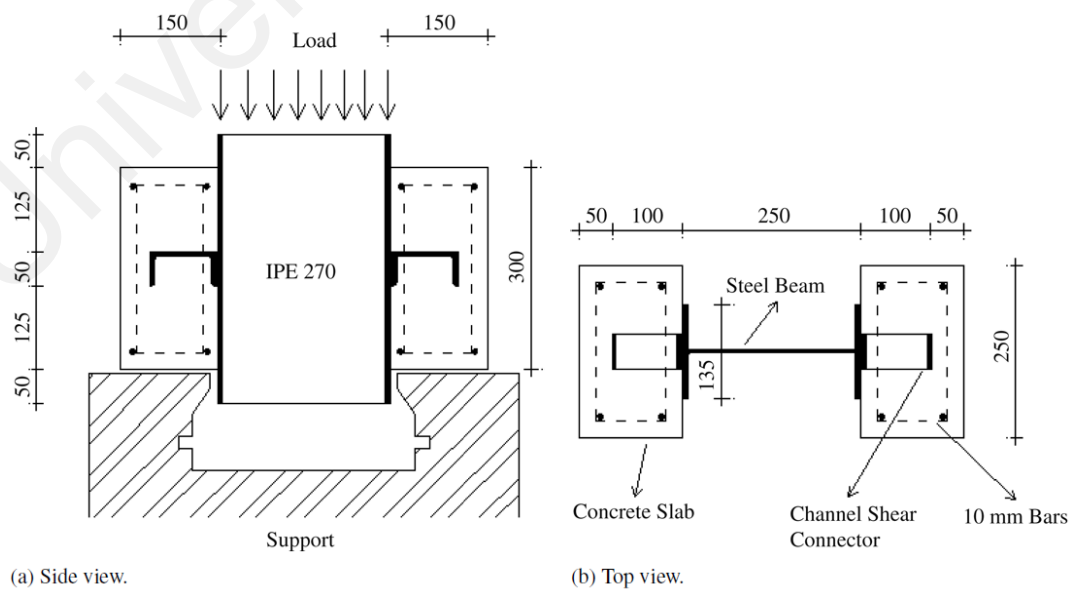

Figure 3.1: The flow chart of methodology

(a) Side view.　　　　　　　　　　(b) Top view.

Figure 3.2: Details of typical specimen used in experimental push-out test (units in mm)

In this study, the concrete compression strength levels were also variable factors. Reinforced high strength and normal strength concrete were used for the purpose of this research. In both HSC mixes, air-dry condition aggregates were used. Graded silica sands with maximum nominal size of 4.75 mm was used as fine aggregate and crushed granite with maximum nominal size of 10 mm was used as coarse aggregate. Ordinary Portland Cement (OPC) which corresponds to the ASTM C150 was used in all mixes. The Rheobuild 1100 was used as a superplasticizer (SP) in both mixes to attain acceptable workability. The SP is dark brown in color with specific gravity of approximately 1.195 and a pH within the range of 6.0 - 9.0. Table 3.1 shows the mix properties of the concrete materials. Short length channels are used due to the limitation in the size of concrete slab (Maleki & Bagheri 2008). In accordance with the site situations, all push-out specimens were cast in a horizontal position. For both sides of specimen slabs, a reliable quality of the concrete was assumed as well. Prior to testing, all specimens were cured in water for 28 days. The steel I beam was painted to avoid corrosion of steel during this time.

Table 3.1: Mix proportions of high strength concrete materials by weight.

Mix no	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)	Silica fume (kg/m^3)	SP (%)	W/C	Modulus of Elasticity (GPA)	Compressive Strength (MPa)
H$_1$	460	910	825	168	40	0.5	0.37	39	82
H$_2$	360	940	870	180	-	1	0.50	32	63

Standard cylinders with 150 mm diameter and 300 mm length and standard cubes with 100 mm length were cast simultaneously with the push-out specimens in order to obtain the compressive strength. Prior to the day of testing, all cylinders and cubes were cured in water. The concrete strength was obtained from both the cylinder and the cubic compression tests. For the purpose of the compressive strength test procedure, the requirements of the ASTM C39 (ASTM, 2005) were used and the mean

values of the concrete compression strength were used in the calculations. For each specimen, five cylinders and ten cubic standard tests were prepared and tested. The average compression test is used for this study.

3.2.1. Loading and test procedure

As shown in Figure 3.3 (a) and (b), a 600 KN capacity universal testing machine was used to apply the load. While loading the slabs, specific support was applied and a load control of 0.04 mm/s was used as the loading rate for all specimens. Prior to every loading procedure, specimens were rearranged to suit the unidirectional nature of the load test frame. In monotonic loading, the load is increased until failure. The steel I beams were positioned on the deck of the universal test machine. Varying the orientation of the channel connector creates a variation in the connector's ultimate strength and relative stiffness (Maleki & Bagheri, 2008b). This fact was considered in the push-out test and at the beginning of every test for all specimens, where the same orientation for channels was considered. The universal test machine automatically records the practical load and relative slip between the I-beam and the concrete block at each time step.
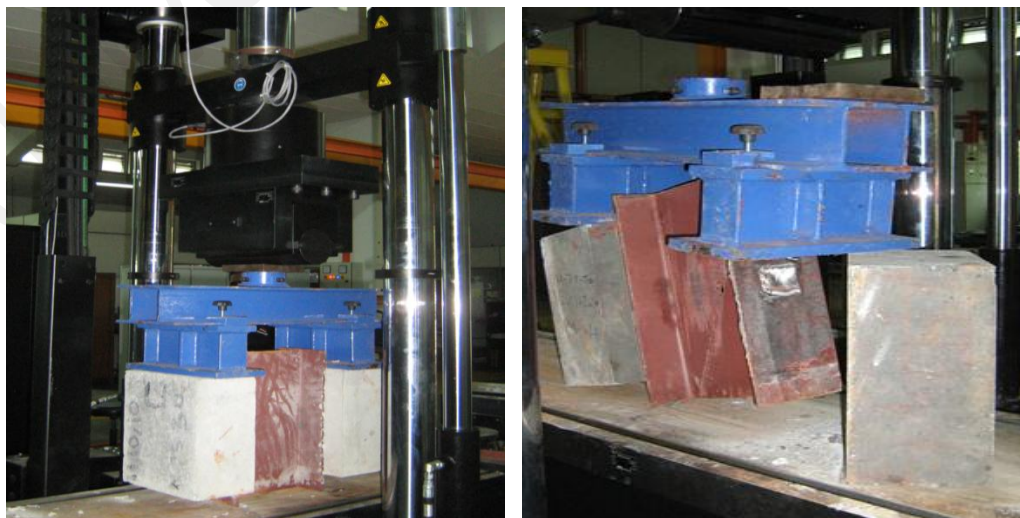
| a) Specimen set up | b) Specimen after fracture |

Figure 3.3: Push-out test setup.

3.3. Numerical method

3.3.1. Data availability

In this research, the data are based on the parameters presented in Table 3.2 and the compression test of concrete used in the slab. The data set involves 1197 data points (instances) that are collected from the push-out tests with each instance being represented by a 5-dimensional real-valued vector. The vector also acts as the input parameters shown in Table 3.2 with the output being its corresponding prediction of shear capacity of the channel shear connectors.

**Table 3.2: Different parameters of tested channel shear connectors**

Input Parameters					Output parameter
Slip	t_f	t_w	f_c	L_c	P

The applied slip between concrete block and steel I-beam, concrete cylinder strength f_c, thickness of channel flange t_f, thickness of channel web t_w, and the length of the channel shear connector (L_c) formed the input parameters, while the output is the shear capacity of the channel shear connector P.

3.3.2. Developing the ANFIS model for the prediction of shear capacity of channel shear connectors

First of all, the data are normalized through the use of a Gaussian normalization technique. Subsequently, a random selection was conducted where 80% of the normalized data were chosen as training data and the remainder of 20% as testing data. As mentioned earlier, the ANFIS models with different parameters (total five) as inputs are implemented with the use of the MATLAB programming language version R2010a. For the purpose of generating the FIS structures, Genfis2 function based on subtractive clustering method is used. In order to determine the best structure with the appropriate membership function parameters, two processes are involved namely 'Learning' and

'Testing'. Throughout the learning process, the membership functions of the inputs are primarily generated using subtractive clustering. Then, a back propagation algorithm in combination with a recursive least squares method are used for the tuning of the membership function parameters. This is followed by the testing step where the generalization capability of the generated model is inspected. The number of membership functions was gradually increased to reduce the Mean Square Error (MSE) obtained by this method. This is done by lowering the range of influence of cluster centers in a trial and error and step by step manner. The structure of implemented ANFIS is illustrated in Figure 3.4.
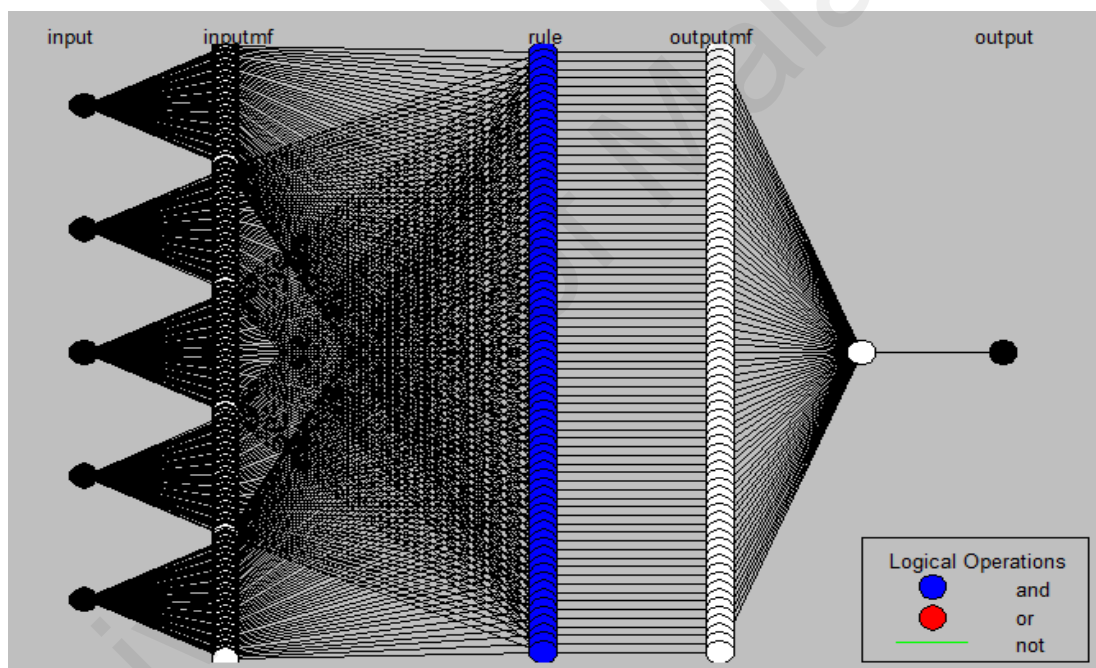
Figure 3.4: Structure of implementing ANFIS (Jang, 1993)

3.4. Results of numerical analysis

Linear Regression (LR) is a scheme that is excellent, simple and yet effective and is used to predict domains with numeric attributes. The linear models operate as building blocks for learning tasks that are more complex. In order to establish a

relationship between the input and output data for the proposed ANFIS modelling, LR analysis is carried out.

The MSE and Correlation Coefficient (R) values are used to evaluate the comparative methods in this study. MSE is a risk function which corresponds to the expected value of the squared error loss or quadratic loss while R is the degree of success in reducing standard deviation (SD). It is used extensively in the sciences as a measure of the strength of linear dependence between two variables. The MSE and R2 is calculated in

Eq. 4.1 as follows:

$$R^2 = 1 - \frac{\sum_{k=1}^{L}(y(k) - \hat{y}(k))^2}{\sum_{k=1}^{L}(y(k) - y_{ave})^2} \qquad \text{(Eq.3.1)}$$

where $\hat{y}(k)$, $y(k)$ and y_{ave} are the output predicted by ANFIS, actual (observed) output and averaged actual output, respectively, and L is the total number of training/testing instances.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Experimental results

Normally, the behavior of shorter channels differs than that of the longer channels. Slabs with longer channels experience concrete cracking on the sides of the slabs when channel fracture occurs, but such is not the case with slabs with shorter channels. Hence, it can be assumed that in a similar condition, concrete cracks more in specimens with longer channel embedded into it. In recent studies conducted by Maleki et al. (Maleki & Bagheri, 2008a; Maleki & Mahoutian, 2009; Shariati, et al., 2010), this matter was also observed in other types of concrete.

4.1.1. Failure type

The most common types of failure of shear connectors identified by the literature are the connector fracture and the crushing and splitting of the concrete element. For the specimens embedded in HSC, channel fracture as illustrated in Figure 4.1 was observed. Channel failure mechanism can be defined when channel web yield and subsequently fracture close to the bottom flange fillet. This failure mode does not depend upon the type of concrete. The growth in load with the square root of compressive strength of concrete was presented by Pashan, (2006) and also observed in this study. Channel fracture failure is also associated with the type of reinforcement in specimens. A similar failure was observed for all the specimens subjected to static and cyclic loading.

The influence connector's height can be assessed not only by taking into consideration the height of the channel but by considering pairs of similar specimens as well. In this case, there are two different types of HSCs, each with two similar pairs of channel embedded into it. For each series, the height of the connector changed from 75

mm to 100 mm. The specimen with the 100 mm high channel connectors carried a slightly higher load compared to the specimens with 75 mm high channel connectors.

a) Fractured channel in slab   b) Fractured channel attached to steel I beam

Figure 4.1: Fracture of channel ($H_1$1003-1).

The load-slip curves of the specimens under monotonic loading can be seen in This might be due to the fact that the shorter channel connectors have a tendency of concentrating the applied load on a smaller area. It can also be seen from the curves that the specimen with 100 mm high channels is more flexible than the one with 75 mm high channels. For the 100 mm high channels, the amount of slip at the ultimate load level was 6.5 - 9 mm as compared to 4 - 8 mm for that of the 75 mm high channels.

For the design of shear connector, static strength is necessary and ductility is an essential assumption which is then confirmed throughout the ultimate slip (displacement) (Shim, 2004).

4.1.2. Ultimate load-slip analysis

The ultimate load-slip for monotonic load of all specimens is shown in Table 4.1. The slip occurs between the I-beam and the concrete block under monotonic and

cyclic loading. Since the slip is larger than 4 mm in all cases, it can be concluded based

from the static curve that there is sufficient ductility for all channel connectors in HSC.

For all specimens, the relative slip is between 4-9 mm at the peak load for the

monotonic loading. Consequently, the different levels of HSC are not significant for the

connector ductility in the HSC push-out test.

Table 4.1: Experimental push-out test results

Specimen	Concrete strength (MPa)	Failure load (KN)	Maximum slip (mm)
$H_1$10050-1	82	175.3	6.5
$H_1$10050-2	82	179.2	5.5
$H_1$10030-1	82	91.8	7.0
$H_1$10030-2	82	95.9	7.0
$H_1$7550-1	82	190.1	5.5
$H_1$7550-2	82	179.0	6.0
$H_1$7530-1	82	117.3	4.5
$H_1$7530-2	82	109.8	4.0
$H_2$10050-1	63	187.6	7.0
$H_2$10050-2	63	187.0	7.5
$H_2$10030-1	63	125.4	7.5
$H_2$10030-2	63	129.2	8.0
$H_2$7550-1	63	190.1	5.0
$H_2$7550-2	63	200.1	6.0
$H_2$7530-1	63	100.6	7.5
$H_2$7530-2	63	86.9	8.0
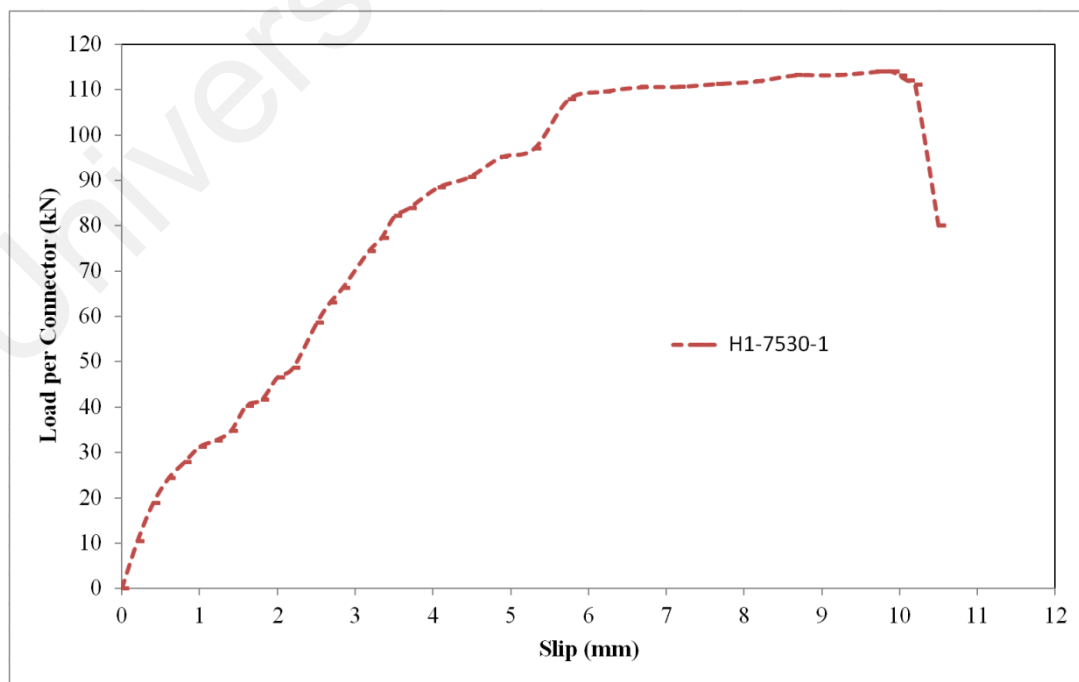
**Figure 4.2: Typical load – slip curve (Specimen $H_1$7530-1)**

4.2. Numerical results

The results of MSE and R^2 obtained using the ANFIS and the LR separately for training and testing data are summarized in Table 4.2.

Table 4.2: Comparison of MSE and R values from ANFIS and LR

Methods	Training Set			Testing set		
	Instances	MSE	R^2	Instances	MSE	R^2
LR	947	0.3949	0.7779	141	0.3357	0.8167
ANFIS	947	0.0687	0.9650	141	0.1271	0.9346

The MSE values derived from ANFIS are more than 2 times smaller compared to the values from the classical linear regression as shown in Table 4.2. Moreover, the R2 value derived from ANFIS for train data is 0.9650 which is an exciting value nearest to 1 for a scientist. The outcome of the experiments demonstrates that the difference between the two comparative methods is more evident for the test set. The prediction of shear capacity of channel shear connectors provided by LR and ANFIS for the test data is shown in Figure 4.2. The actual and predicted data are represented by the horizontal and vertical axes respectively. A direct linear relation between the actual and predicted data should be the outcome of a precise modelling. For the prediction of shear capacity of channel shear connectors, the proposed ANFIS method is highly accurate and precise compared to the classical LR as revealed in Figure 4.2.

(a) ANFIS   (b) Linear regression
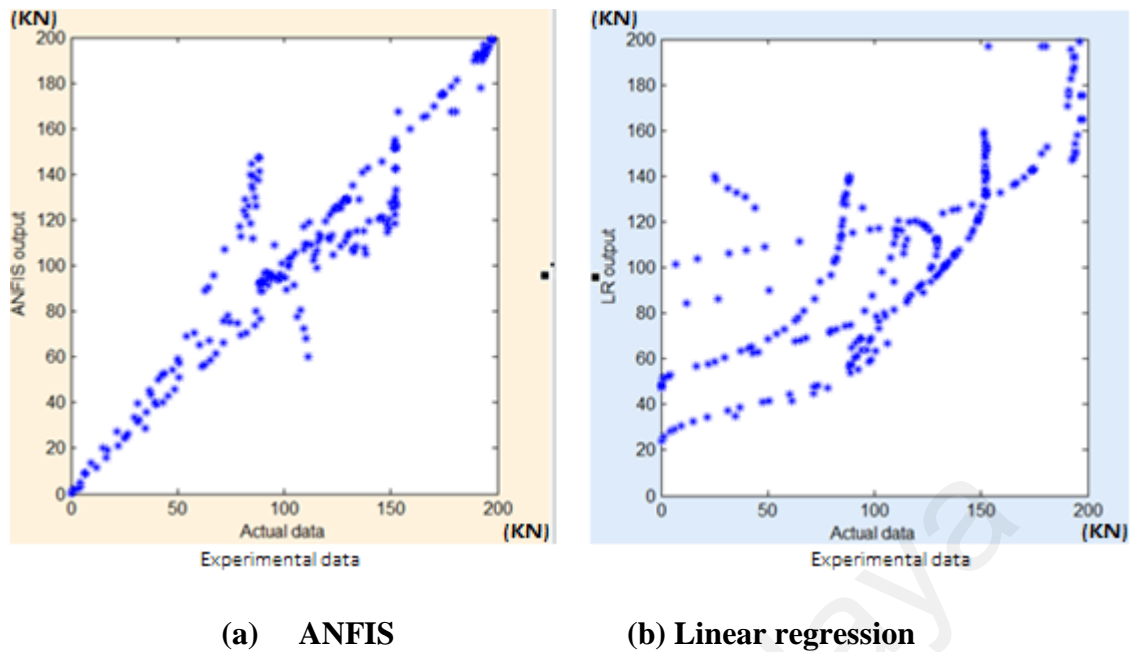
Figure 4.3: The Prediction of shear strength of channel shear connectors with LR and ANFIS

The modelled fuzzy surfaces shown in Figures 4.3 and 4.4 can be used to visualize the relation between input variables and output. The output surface of a FIS model can be examined through the use of a Graphical User Interface (GUI) tool. GUI offers a visual impression of the possible combinations of the two input variables and the output in 3-D which is a fast visual method of analyzing and predicting the shear capacity of channel shear connectors. Based on the data shown in Table 4.2, the FIS provides a mathematical solution to determine the shear capacity of channel shear connectors.

Figures 4.3 and 4.4 illustrate the input-output surfaces, namely the nonlinear and monotonic surfaces, which demonstrate the response of the ANFIS model to changing values on strain in tie section prediction.
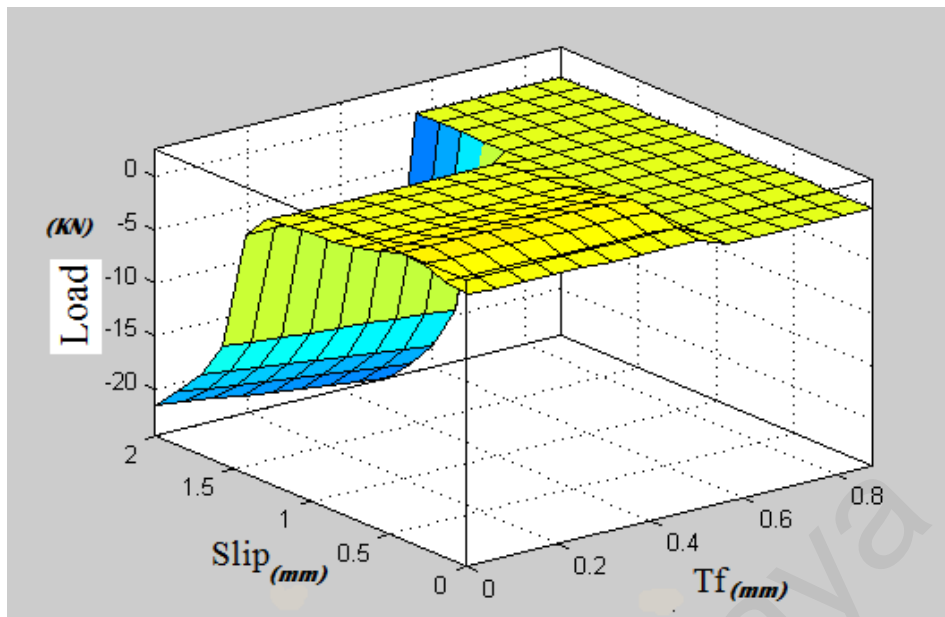
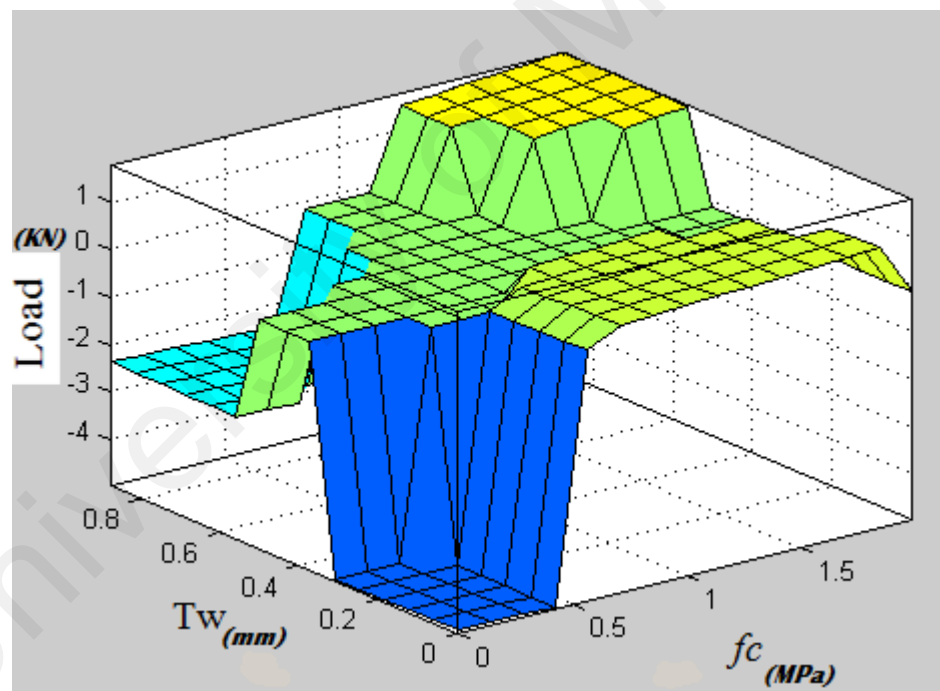**Figure 4.4: Fuzzy surface: slip and t_f versus load prediction**

Figure 4.5: Fuzzy surface: T_w and compressive strength of concrete versus load prediction

4.3. ANFIS selection of the shear strength variables
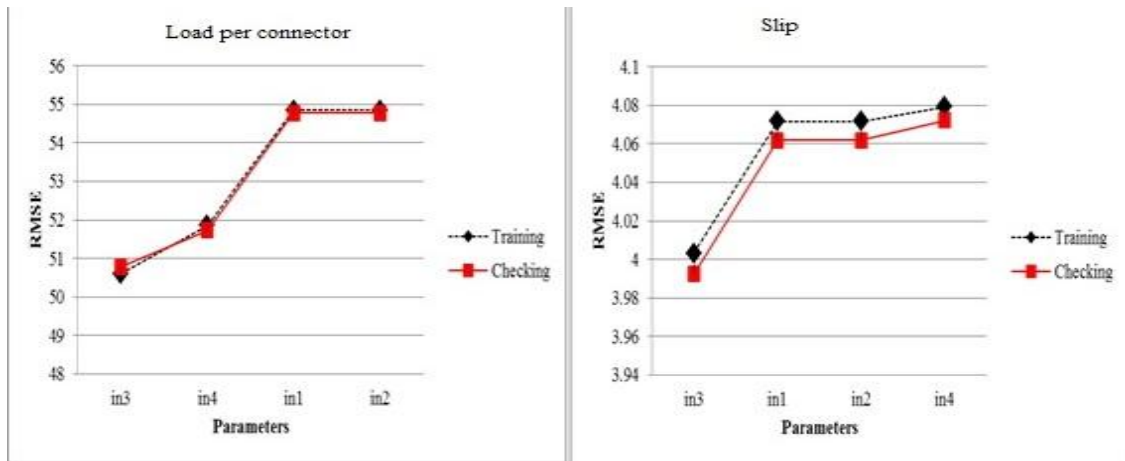
4.3.1. Input variables

In this study, the values of flange thickness, web thickness, concrete compression strength and connector length was used for generating ANFIS selection model. To get more reliable evaluation and comparison, ANFIS model are tested by evaluating a data set that was not used during the training process. The statistical parameters for data sets are calculated and given in Tables 4.3 for shear strength estimation. Two shear strength output parameters are analysed: load per connector [KN] and connector slip [mm].

Table 4.3: Statistical parameters for data sets for shear strength estimation

Variable
in1 – Flange thickness
in2 – Web thickness
in3 – Concrete strength
in4 – Connector length

4.3.2. ANFIS analysis of shear strength

A comprehensive search was performed within the available inputs to select the set of the most optimal combinations inputs of the parameters that most influence the output parameters (load per connector and connector slip). Essentially, the functions build an ANFIS model for each combination, trains it for one epoch and reports the performance achieved. In the beginning, the one most influential input in predicting the output was determined (Figure 4.5). The left-most input variables (input 3) have the least error or the most relevance with respect to the output. It means the input with the lease error has the most influence on the load per connector and on the connector slip. The input was concrete compression strength.

Figure 4.6: Input parameter's influence on the shear strength and slip

The plots and results in Figure 4.6 clearly indicate that the number 3 input variable means concrete compression strength is the most influential parameter for load per connector estimation and for the connector slip estimation. The training and checking errors are comparable, which indirectly suggests that there is no over fitting. This means it can be increased and explored to select more than one input parameter to build the ANFIS model. To verify this, search can be performed for the optimal combination of two input parameters. Table 4.4 shows results for connector slip analyses for combinations of the two variables. Referring to the Table 4.4., in general, the combination of input variables connector length and concrete compression strength are the most influential for connector slip prediction since the training error was the smallest for this combination. Table 4.5 show results for load per connector analysis for combinations of the two variables. Again, the combination of input number 3 and 4 means connector length and concrete compression strength are the most influential also for load per connector prediction. The above results can be claimed from above Tables from MATLAB software analysis by comparing the MSE and R^2.

It may not be appropriate to use more than two inputs for building the ANFIS model since a model with a simple structure was always preferred. Therefore emphasis will be focused to the two-input ANFIS for further examination. The selected two input

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parameters from the original training and checking datasets were then extracted for further analysing.

Table 4.4: Statistical results for data sets for connector slip estimation

Slip (mm)	Flange thickness	Web thickness	Concrete compression strength	Connector length
Flange thickness	trn=4.0716, chk=4.0618	trn=4.0716, chk=4.0618	trn=4.0029, chk=3.9918	trn=4.0476, chk=4.0347
Web thickness		trn=4.0716, chk=4.0618	trn=4.0029, chk=3.9918	trn=4.0476, chk=4.0347
Concrete compression strength			trn=4.0031, chk=3.9923	trn=4.0026, chk=3.9915
Connector length				trn=4.0794, chk=4.0722

**Table 4.5: Statistical results for data sets for load per connector estimation**

Load (KN)	Flange thickness	Web thickness	Concrete compression strength	Connector length
Flange thickness	trn=54.8504, chk=54.7802	trn=54.8504, chk=54.7802	trn=50.0190, chk=50.1793	trn=49.5103, chk=49.4609
Web thickness		trn=54.8504, chk=54.7802	trn=50.0190, chk=50.1793	trn=49.5103, chk=49.4609
Concrete compression strength			trn=50.6102, chk=50.7785	trn=46.8081, chk=46.6759
Connector length				trn=51.8584, chk=51.7318

The used function for all parameters only trains each ANFIS for a single epoch to be able to quickly find the right inputs. Since the inputs are fixed, the numbers of epoch on ANFIS training can be increased (i.e. 100 epochs).

The input-output surfaces for the two most influential parameters on the load per connector is shown in Figure 4.6 is a nonlinear and monotonic surface and illustrates how the ANFIS model will respond to varying the most influential values.The ANFIS prediction can be compared against a linear regression model by comparing their respective RMSE values against checking data. Linear RMSE regression was 3.995 and ANFIS regression RMSE was 3.991 for connector slip prediction. Linear RMSE regression was 47.326 and ANFIS regression RMSE was 46.676 for load per connector

prediction. It means ANFIS outperforms linear regression for the both parameters (Table 4.3).
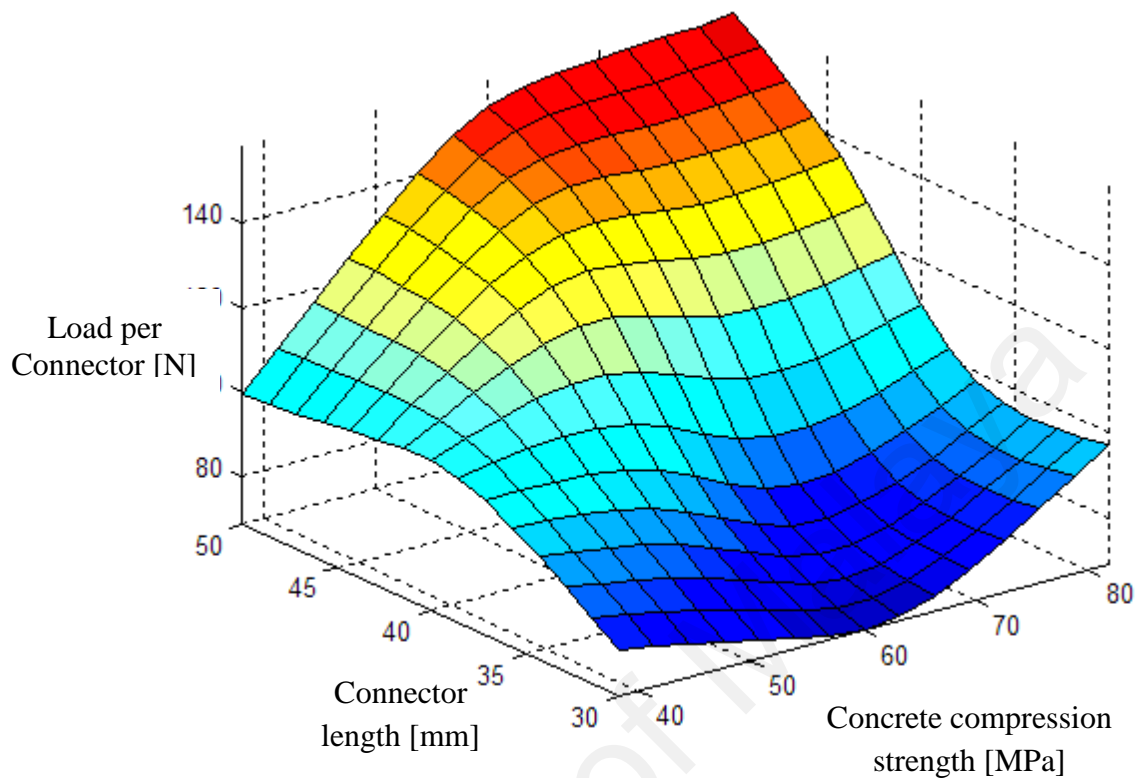
Figure 4.7: Input-output surfaces for the two most influential parameters on the connector Load per connector
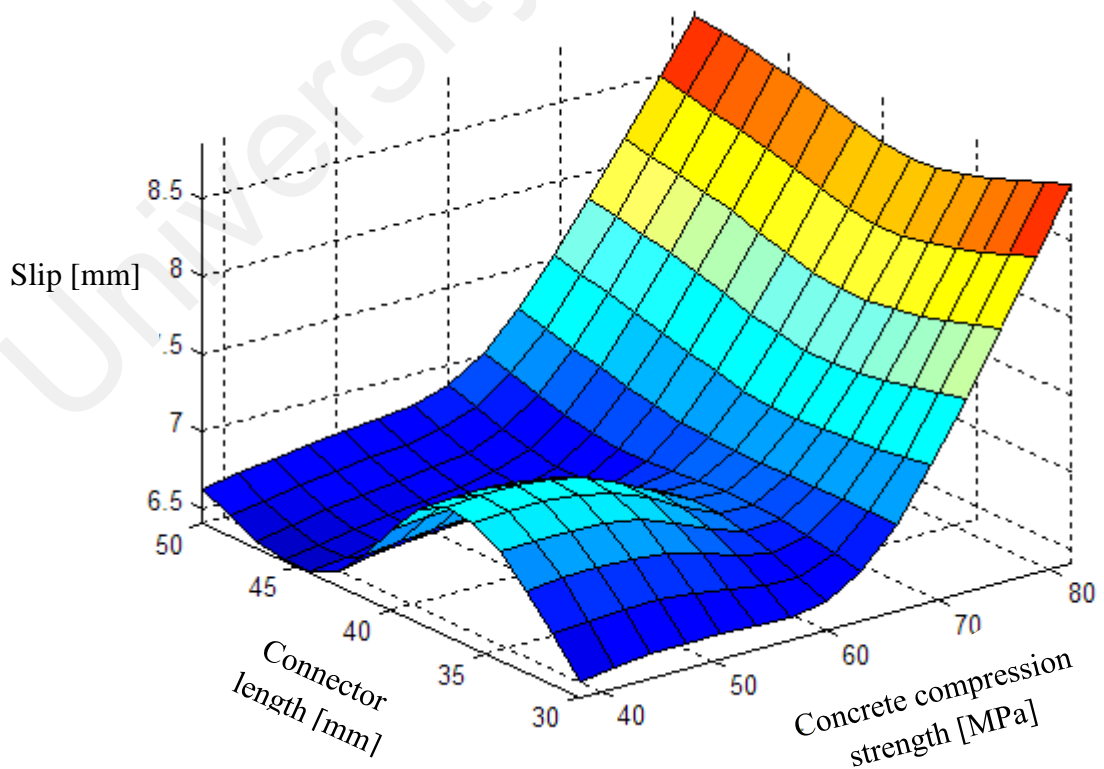
Figure 4.8: Input-Output surface for trained FIS for connector slip prediction

CHAPTER 5. CONCLUSION

5.1. Conclusions and recommendations

Even though shear studs are the most widely used shear connectors in composite beams, channel connectors present improvements and advantages over shear studs. For many years, research focused on generating better formulas to predict the ultimate load capacity for channel shear connectors. However, most of the research did not include the European sections and had problems with the equations. But with the study done by Baran and Topkaya (2012) a new inclusive formula was introduced in the result of a push-out test study with European channel sections as shear connectors.

Due to its complex behavior and lack of valid approaches, the prediction of shear capacity of channel shear connectors is very difficult. In this study, the researcher examined and compared the use of ANFIS as LR in predicting the shear capacity of channel shear connectors. The outcome showed that the proposed model offers adequate prediction of the shear capacity of channel shear connectors at varying slip, flange of web and thickness, length and concrete compression strength. For both training and testing sets, the value of MSE derived from ANFIS is more than two times times lesser than that of LR and thus more accurate than the classical LR. In conclusion, for the purpose of predicting the shear capacity of channel shear connectors, the performance comparison of both ANFIS and LR for the test data shows that the proposed ANFIS method is more accurate than the classical LR.

This investigation also described the selection of the parameters which effect on shear strength prediction by using ANFIS methodology. Fuzzy variables can overcome the difficulties in predicting most important parameters. In this study, a systematic approach of selecting the most influential parameters on the shear strength of the connectors by means of ANFIS strategy was investigated. The

main advantage of designing the ANFIS coordination scheme is to estimate the most important parameters as a very important criterion for overall shear strength estimation and prediction. Simulations were run in MATLAB and the results were observed on the corresponding output blocks. The main advantages of the ANFIS scheme are: computationally efficient, well-adaptable with optimization and adaptive techniques. This can also be combined with expert systems and rough sets for other applications. ANFIS can also be used with systems handling more complex parameters. Another advantage of ANFIS is its speed of operation, which is much faster than in other control strategies; the tedious task of training membership functions is done in ANFIS.

The inclusion of many input variables, however, has many drawbacks: explaining the model is difficult, irrelevant variables act as noise, deteriorating the generalization capability of the model and data collecting can be much more costly. It is therefore useful to invent methods, which allow reducing the number of input variables, thus reducing the complexity of the model, and possibly gaining better predictive performances and insights into the relevance of the variables for the problem. The obtained results show that the input variable Concrete compression strength is the most influential for shear strength prediction of the connectors.

For future work, it is recommended to study the effect of using a shear stud without threads and nuts but welded directly to the steel parts and to make comparison between these two cases. It is also recommended to study the effect of compressive strength of concrete, effect of impact loading, fatigue loading or fire on the behavior of the connectors. Furthermore, it is recommended that further research on shear connectors of different heights should be carried out in order to develop a general equation which would be able to predict the shear capacity of the connectors of different height at elevated temperatures.

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