CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the literature reviews focus on the technical aspects starting from the reinforced concrete structure strengthening applications and durability problems identification, site exposure weathering characteristics, Fibre Reinforced Polymer (FRP) composites technology and applications, adhesive bonding technology, to the development of test rigs for experimentation purposes that have been developed and applied by past researchers. The importance of focusing on these aspects is that they are the key elements in answering the study programme objectives.

2.2 The Technology and Application of Fibre Reinforced Polymer or Steel Plate Bonded System in Construction Industry

The technique for strengthening structures such as reinforced concrete beam, column and slab by method of bonding of FRP Plate or laminating of FRP fabric system is slowly being accepted by the Malaysian authority over the past few years. Table 2.1 shows a list of selected projects that were undertaken by FOSROC Sdn. Bhd. [2], i.e. one of the leading companies that deal with strengthening works in Malaysia.

The technique has proven to be successful when applied in most European countries and in the United States of America, and has been referred to as a technological benchmark to be used in Malaysia. The main concept of applying this technique for damaged or deteriorated structures is to strengthen and stiffen the stress-critical areas. The advantages of using FRP composites for this kind of application compared to the existing conventional technique of using steel plates are FRP is lighter than steel and also immune to atmospheric and to electro-chemical corrosion [1]. Besides that, FRP composite also offers flexibility on site handling and flexibility in applying onto irregular structured shapes.

Table 2.1: List of projects using FRP for structures rehabilitation in Malaysia [2]

NO	PROJECT	APPLICATION	YEAR
1	Rehabilitation/Strengthening Works to Muar Bridge At Muar, Johor. (Fosroc SK-N200)	R.C.Beams	2001
2	Rehabilitation/Strengthening Works to Kuala Besut Bridge At Terengganu. (Fosroc SK-N200)	R.C.Beams & Slabs	2001
3	Rehabilitation/Strengthening Works to Muar Bridge, Johor. (Fosroc SK-N200)	R.C.Columns	2002
4	Strengthening Works to AIA Building At Jalan Ampang, Kuala Lumpur. (Fosroc SK-N300)	R.C.Beams	2002
5	Strengthening Works to Beams At Cyberia Homes, Cyberjaya. (Fosroc SK-N300)	R.C.Beams	2002
6	Rehabilitation/Strengthening Works to Kuala Besut Bridge At Terengganu. (Fosroc SK-N200)	R.C.Beams & Slabs	2003
7	Rehabilitation/Strengthening Works to Chukai Bridge, Terengganu. (Fosroc SK-N200)	R.C.Beams	2003
8	Strengthening Works to R.C.Beams at Cyberjaya For Kenwin Engineering Sdn Bhd, Cyberjaya. (Fosroc SK-N300)	R.C.Beams	2003
9	Strengthening Works to Beams at Palace of Justice, Putrajaya. (Fosroc SK-N300)	R.C.Beams	2003
10	Rehabilitation/Strengthening Works to Dungun Bridge, Terengganu. (Fosroc SK-N200)	R.C.Beams	2003
11	Strengthening Works to Muar Bridge at Muar, Johor. (Fosroc SK-N200)	R.C.Columns	2005

The long-term durability of any construction material is a key element in ensuring that a structure is able to maintain its integrity and provides the service according to its design throughout its service life. Deteriorated concrete structures require repair and maintenance or sometimes need strengthening to extend their service life. The development of epoxy material as an adhesive system since 1960s has shown a great potential for strengthening of existing reinforced concrete structures by externally bonded steel plate technique [3]. In the area of strengthening deteriorated reinforced concrete members the steel plate-bonding system has been widely used and proven to be the most successful externally repair technique. Figure 2.1 shows an example of the application of steel plate bonded to the tension face of reinforced concrete beam at site.

Fig. 2.1: Steel plate member used for strengthening RC beam [4]

From a survey conducted by McKenna and Erki [5], it showed that steel plate bonded system has been used since 1964, when malleable steel plates bonded with adhesive were applied to load bearing structures of an apartment building, in Durban, South Africa. The same system was also applied for upgrading several buildings in Switzerland in early 1970s and Tee-beam bridges in France in 1972 and 1974. The survey also reported that in Japan over 200 highway bridges had been strengthened with steel plate bonded with epoxy together with anchorage bolted system. Most of the problems with existing structure members are due to poor design, inadequate reinforcement, corrosion and creep. The survey also indicated that the steel plates epoxy bonded system was quite successfully used to rehabilitate a wide range of structural problems over the last 30 over years.

However, due to possible corrosion problem and handling aspect during installation of steel plates, other techniques are being investigated. Nowadays, with the advancement in the material technology an advanced composite material or technically known as Fibre Reinforced Polymer (FRP) shows a great potential to be used for renewal programmes in the construction industry for the rehabilitation work throughout the world [6]. Figure 2.2 shows the laminating technique of Carbon Fibre Reinforced Polymer (CFRP) onto a reinforced concrete beam tension surface. In addition, Figure 2.3 shows the application of CFRP sheets for rehabilitation of damaged bridge beams.

Fig. 2.2: FRP laminate system used for strengthening RC beam [7]

Fig. 2.3: Muar Bridge Beams strengthened with CFRP Sheet [2]

2.2.1 Definition of Durability

The durability of a material or a structure is defined as the ability to resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions [6,8].

2.2.2 Bond Durability of Steel Plate as Externally Bonded System

In the area of steel plate bonding system numerous researches have been carried out and the knowledge on the long-term performance of the system is well established. Results have shown that the maximum composite action could be achieved by the adhesive joint, together with significant improvement in performance in terms of ultimate load, stiffness and crack control [1]. However, an exposure test that was carried out indicated that a significant amount of corrosion of steel could take place during exposure at site [1]. A localized bond failure due to corrosion resulting in loss of bond strength at the steel-epoxy interface was observed and the reduction of the overall strength of the exposed beams was attributed to corrosion [9]. Finally, it can be concluded that the use of externally bonded steel plate to rehabilitate reinforced concrete structures has shown some disadvantages since it is difficult to handle at site and also sensitive to aggressive environments.

2.2.3 Bond Durability of Fibre Reinforced Polymer Plate/Laminate to Concrete Bonded System

The FRP plate bonding system whether using CFRP or GFRP plate, is seen to be applicable as a strengthening technique, but several aspects of structural implications and long-term behaviour and durability of the system need to be understood and designed for before such technique can be widely applied. In addition, the long-term durability of the plate-adhesive and concrete-adhesive interface exposed to tropical environment with heavy rain and sunshine throughout the year is an important factor to determine the suitability of the FRP plate-bonded system to be used in this region. Long-term durability is one of the most important properties of most polymeric based adhesive bonds. Although it can be difficult to achieve in aggressive environments, there are some methods to delay the degradation process. Material selection, proper surface preparation and the right joint design are able to increase and maintain the durability of joints. Such study is essential for any modification or recommendation, if necessary, pertaining to the use of the FRP plate bonding system, in particular using the CFRP plate.

In contrast to steel, CFRP plate is seen to be more durable to the most aggressive environment where corrosion problem faced by the steel plate bonding system can be eliminated. However, the CFRP plate-bonded system is a relatively new technology in the construction industry even though the design concept is quite similar to the steel plate bonding system. Therefore, there are still many areas of material and structural implication arising from the use of CFRP plates-bonded system that are not yet clear and need further research especially in durability aspects [10]. Furthermore, most of the studies have been conducted in Japan, Europe, Canada and the United States of America, in which the weather pattern is relatively different from tropical environment. Researches on the short-term structural performance of reinforced concrete beams strengthened with CFRP plate bonded system that have been conducted showed a significant improvement in the ultimate flexural capacity of the beams [11]. Another testing programme on strengthening of undamaged beams with FRP plates demonstrated that bonded FRP plates improved the strength and stiffness of reinforced concrete beams [12].

Many researches have been conducted the flexural behaviour of reinforced concrete beams strengthened on the tension face with either GFRP or CFRP plates and fabric wet lay-up system. The findings showed that due to higher tensile strength and higher modulus of elasticity of CFRP plate compared to GFRP plate, the overall structural performance of reinforced concrete beams strengthened with CFRP plate was better than GFRP plate. The typical failure mechanisms of the strengthened beams were plate peeling or debonding close to the plate ends, flexural tensile cracks in concrete with rupture of FRP plate and shear cracks in concrete starting from the plate ends [13]. Due to the abrupt curtailment of the plate-adhesive system adjacent to the support a high concentration of interface shear stress in the vicinity of the plate occurred [14]. This led to abrupt and non-ductile failure of the member, which was undesirable in the design. It could be seen that the bond between adhesive-FRP plate and adhesive-concrete interface was of particular importance for the member to develop maximum flexural capacity and affected the long-term performance of the strengthened member. Toutanji and Gomez [15] in their durability study of FRP composites bonded to concrete beams have shown that exposure to salt water and dry condition at 35°C under 90% humidity under wet/dry cycles have exhibited less improvement in terms of ratio of ultimate load for both exposed and control specimens as shown in Table 2.2. The load deflection behaviour of beams strengthened with CFRP and GFRP sheet are shown in Fig. 2.4 and Fig. 2.5. The debonding of FRP sheets from concrete interface were shown by all FRP bonded beams.

Table 2.2: Experimental results of control and exposed beams [15]

Beam	Epoxy type	Ultimate load (kN) (room conditioning)	Fr*/Fr[a]	Ultimate load (kN) (wet/dry conditioning)	Fr*/Fr[b]
000	-	2.2	-	2.7	-
C1II	I	8.0	3.7	6.7	2.5
C1II	II	8.7	4.0	9.6	3.6
C1III	III	6.8	3.1	7.8	2.9
C2I	I	9.8	4.5	8.9	3.3
C2II	II	11.3	5.1	12.0	4.4
C2III	III	7.9	3.6	9.0	3.3
G1I	I	6.3	2.9	5.5	2.1
G1II	II	6.5	3.0	6.1	2.3
G1III	III	4.8	2.2	5.8	2.1
G2I	I	7.7	3.5	7.7	2.9
G2II	II	8.9	4.1	9.9	3.7
G2III	III	8.0	3.6	9.2	3.4

Fr*/Fr[a] : ratio of ultimate load of FRP bonded beams to that of unbonded at room temperature.

Fr*/Fr[b] : ratio of ultimate load of FRP bonded beams to that of unbonded under wet/dry conditions.

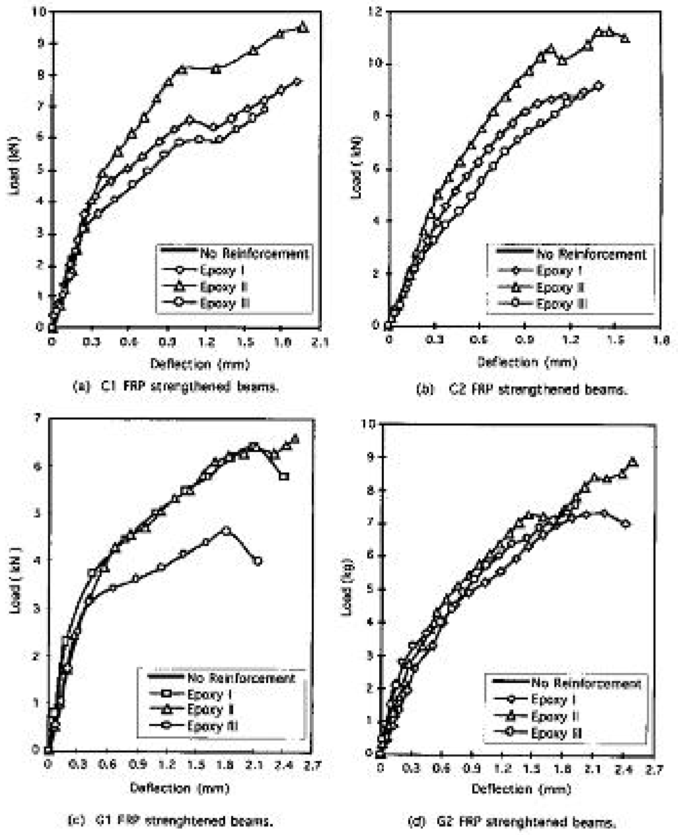


Fig. 2.4: Typical behaviour of load versus deflection for control beams [15]

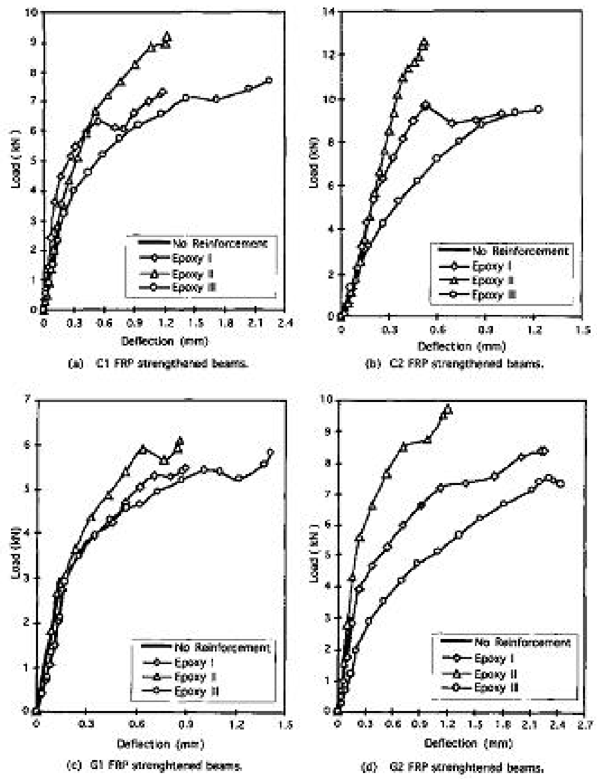


Fig. 2.5: Typical behaviour of load versus deflection for exposure beams under wet/dry cycles [15]

A similar study was also conducted by Chajes, *et al.* [16] on durability of concrete beams externally bonded with aramid, glass and carbon composites. The externally bonded beam specimens were exposed to freeze/thaw and calcium chloride solution under wet/dry conditions. The results showed that the effects of aggressive environments degraded the FRP externally bonded beam strength performances. The beams bonded with aramid and glass fibre system exhibited about 50% reduction of strength due to both exposure conditions.

Experimental study conducted by Karbhari and Zhao [17] have shown that the effect of exposure conditions on composite and composite-concrete interfaces was degradation due to moisture uptake. Their study involved the application of GFRP and CFRP composites that were externally bonded to the tension face of concrete beam specimens. The specimens were exposed to fresh water, salt water, freeze/thaw and below freezing temperature. The flexural load test results indicated that the degradation occurred primarily at the interface level of FRP-concrete and FRP itself due to changes in composite stiffness caused by resin plasticization. They also discovered that the moisture absorption rate was high in exposure to fresh water compared to sea water.

On the other hand, very little research has been conducted on the long-term performance of reinforced concrete beams strengthened using FRP plate-bonded system exposed to natural weather. Thus, this area needs further investigation especially with different exposure conditions. In relation to that, the long-term durability of the FRP-plate bonded system exposed to different aggressive environments needs to be addressed especially exposure to tropical climate in which at present the data are very limited or non-existent. In the plate bonding system penetration of moisture may also occur through the resin via micro cracks, which can lead to local debonding of the FRP plate. Furthermore, most of the FRP reinforcements that have been developed in temperate countries were tested for durability under conditions simulating those countries. Since the tropical climate experiences abundant rain and sunshine throughout the year, it would be essential to assess the long-term durability of the FRP plate-bonded system in this Southeast Asian region [18].

The environmental resistance of any bonded assembly of FRP system depends on the durability of the individual components materials, as well as on the bond between them [19]. For example, in the use of FRP plate as a material for external strengthening of reinforced concrete structures, the individual components are the reinforced concrete, the FRP and the adhesive. The long-term integrity of bonded joints implies both chemical and mechanical durability under varying temperatures, moisture and other environmental factors. Adhesive bonded joints with equivalent bond strength values in short-term static tests may differ markedly with respect to the durability.

The measured residual joint strength after environmental exposure is a function of change in the cohesive properties of the adherend and in the adhesion between the adhesives and the adherend. Therefore, joint durability demands a three-fold consideration of the structural integrity of the cured adhesive, the adherends and the environmental stability of the interface [19].

Adhesive bonded joints are generally attacked by exposure to moisture and elevated temperature. In a well mode joint where a good bond has been achieved, the main element that needs attention is the adhesive layer. A small amount of moisture will induce plasticization of the adhesive in highly stressed regions and may actually be beneficial in reducing stress concentrations. However, a small reduction in joint strength should normally be anticipated in relation to the effects of environmental conditions on the adhesive itself [19].

2.2.4 Factors Affecting Fibre Reinforced Polymer-Concrete Bond Strength

The strength of a joint depends on the tensile yield strength (i.e. for ductile materials), its modulus and thickness of the adherend as well as shear modulus and the thickness of the adhesive. The adhesive layer must be as thin as possible to avoid joint starvation and the shear modulus should be high in order to provide joint toughness (i.e. able to absorb or resist stresses at the bond interface). The study of bond performances of steel or FRP plates or FRP laminate system with concrete can best be referred to the research works conducted by Swamy *et al.* [20,21], Jones *et al.* [14] and Roberts [22]. It can be concluded that there is no consistent relationship between peak bond stress and average bond strength or between peak bond stress and concrete strength. The study conducted by Horiguchi and Saeki [23] found that the shear test method exhibited the lowest bond strength relative to compressive strength of the concrete. The shear test method showed a relatively low bond strength and less effect towards the concrete compressive strength. The type of failure mode was dominated by debonding between CFRP and concrete interface. However, those studies did not focus on other factors such as concrete surface preparation, local force distribution, local strains and the durability aspect (long-term effect).

Toutanji and Ortiz [24] in their study found that the cracks occurred on the bonded FRP-concrete prism for all test specimens. The measured strains, i.e. at the centre of test specimen, on FRP sheets gradually increased from the centre towards the outside, i.e. due to the formation or development of cracks at concrete surface where the separation occurred and slowly widened and finally led to the final concrete fracture. It showed that final concrete fracture has occurred at the FRP-concrete interface. The concrete surface preparation by water jet treatment on concrete surface has shown a 50% higher load up to failure compared to sanding method. They also found that a high modulus of CFRP composite produced bond strength of about 25% higher than low modulus type. Their finding also showed that the fibre stiffness and concrete surface treatment were the main factors contributing to specimen stiffness after the first cracking as shown in Fig. 2.6 and Fig. 2.7 respectively.

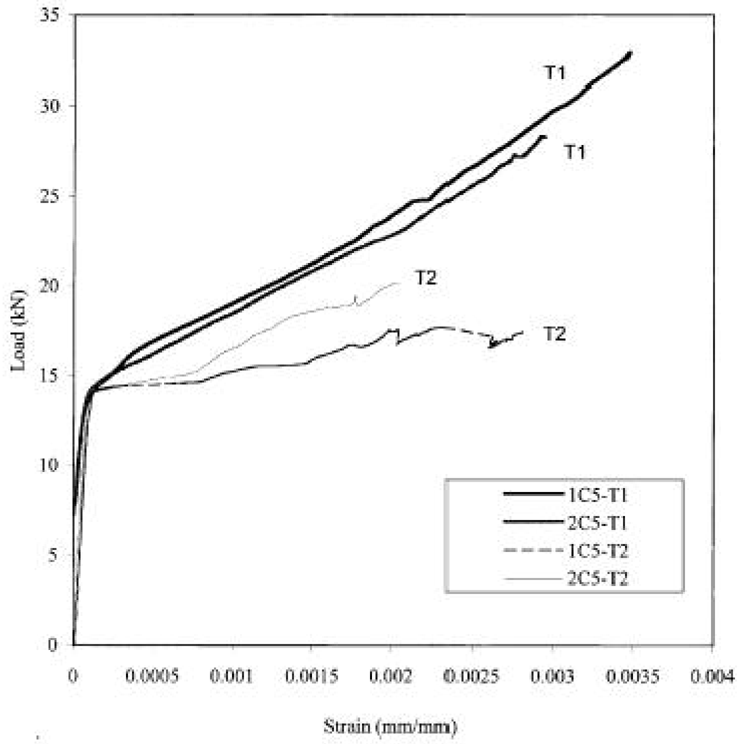


Fig. 2.6: Typical load-strain bi-linear curve for FRP sheet-concrete prism bonded specimen [24]

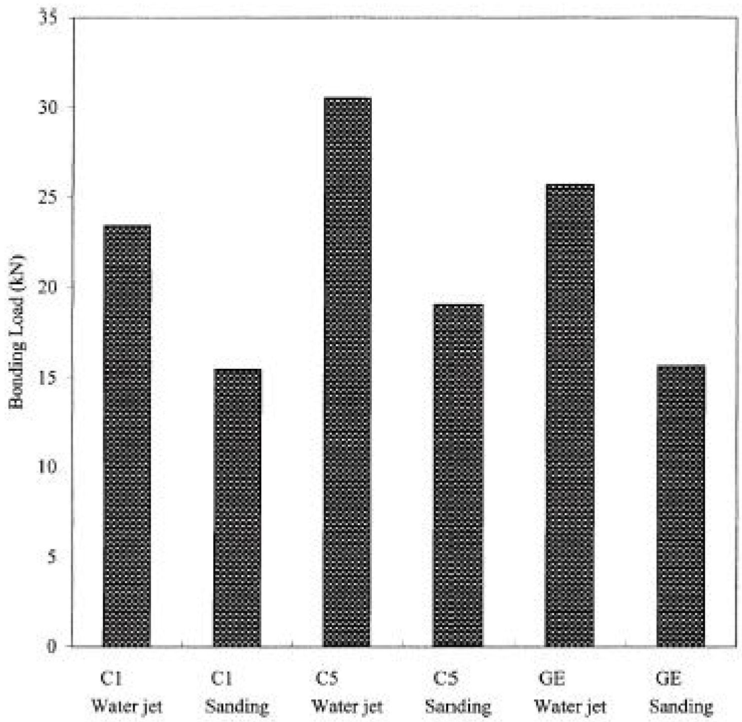


Fig. 2.7: Comparison of bond strength due to different concrete surface preparation methods [24]

Arden and Nanny [25] in their research finding have shown that the reinforced concrete beam surface preparation by sandblasting method has slightly improved their ultimate failure load and the beam stiffness compared to the tested beam treated by sanding method. It could be estimated that the increase in failure load and deflection were about 20 kN (i.e. about 15%) and 5.5 mm (i.e. about 79%), respectively. Failure at the adhesive-concrete interface occurred on each tested beam. The failure initially started within the constant moment region which started by cracks development that produced high stress level at bond interface at a high load. This implied that failure started at bond interface that finally propagated towards the sheet end. Their finding also concluded that pre-cracked concrete beams surface treatments produced negligible effects in the increment of the ultimate failure loads and deflections.

2.2.5 Factors Affecting Fibre Reinforced Polymer-Concrete Bond Durability

One of the most important factors in bond durability is the environmental stability factor occuring at adhesive-adherend interfaces. The changes in the adhesive and the adherend mechanical or chemical properties can be the factors that allowed for changes in adhesion properties. Therefore, bond surface conditions and pre-treatments often represent the key to enhancing the bond durability. In FRP-concrete bonded system for example, if the bonding procedure is well followed, the surfaces of both concrete and FRP materials are relatively stable; finally the durable bonds with epoxy adhesives can be achieved. The substitution of FRP materials for steel in strengthening reinforced concrete members is motivated by the assurance of superior bond integrity.

The most outstanding durability study was conducted by Mukhopadhyaya *et al.* [10] on GFRP-epoxy-concrete exposed to various selected aggressive conditions. They used two different concrete mixes with compressive strength of 35 MPa and 50 MPa for mix A and B respectively. They discovered that aggressive environmental conditions, i.e. wet and dry cycles and freeze/thaw did create further damage to the plate-concrete-adhesive interfaces. All the specimens exposed to aggressive regimes showed higher dimensional changes and differential movement between the plate and concrete compared to the control specimens. They also found that the exposure regime had a distinct and strong influence on the nature of the bond transfer length. The exposure regime not only increased the length over which the force was transferred from the plate to the concrete, but also progressively increased the process of debonding at the stressed end. The typical bond characteristic found on their study can best be referred to Fig. 2.8 (a) to Fig. 2.8 (d), and from Fig. 2.9 (a) to Fig. 2.9 (d).

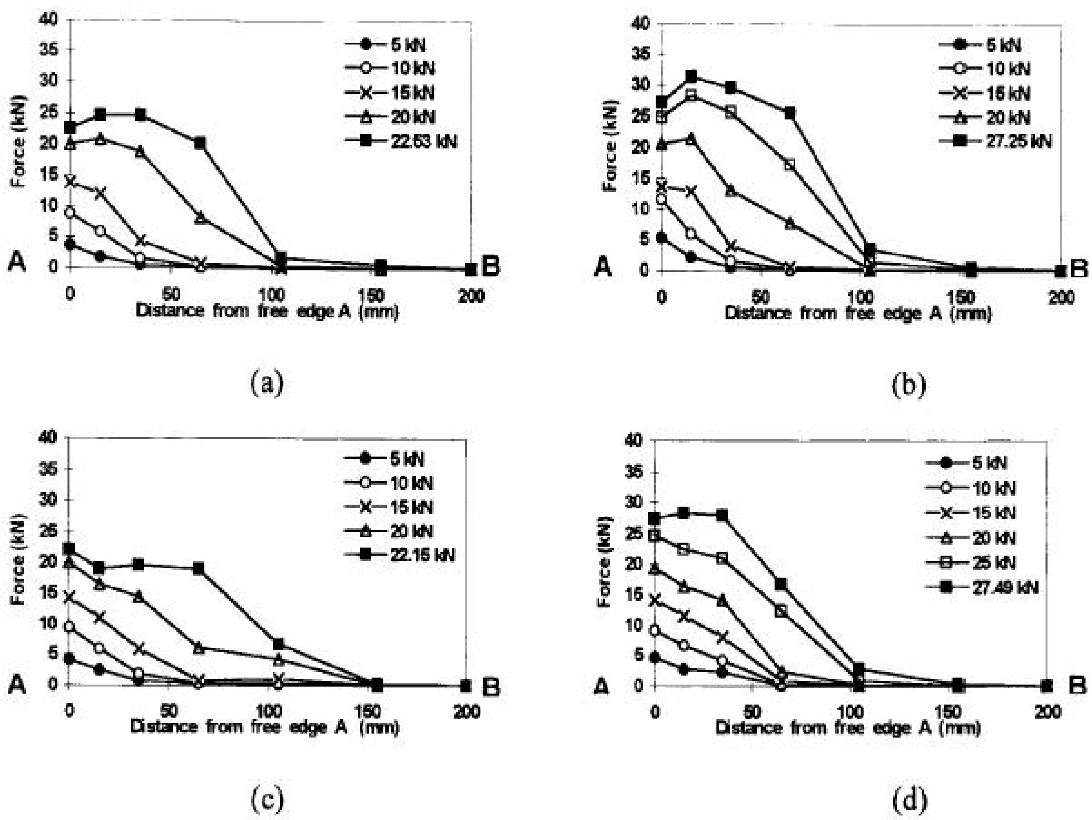


Fig. 2.8: Typical force transfer distributions for concrete mix A: (a) control; (b) wet/dry; (c) freeze/thaw; and (d) dual [10]

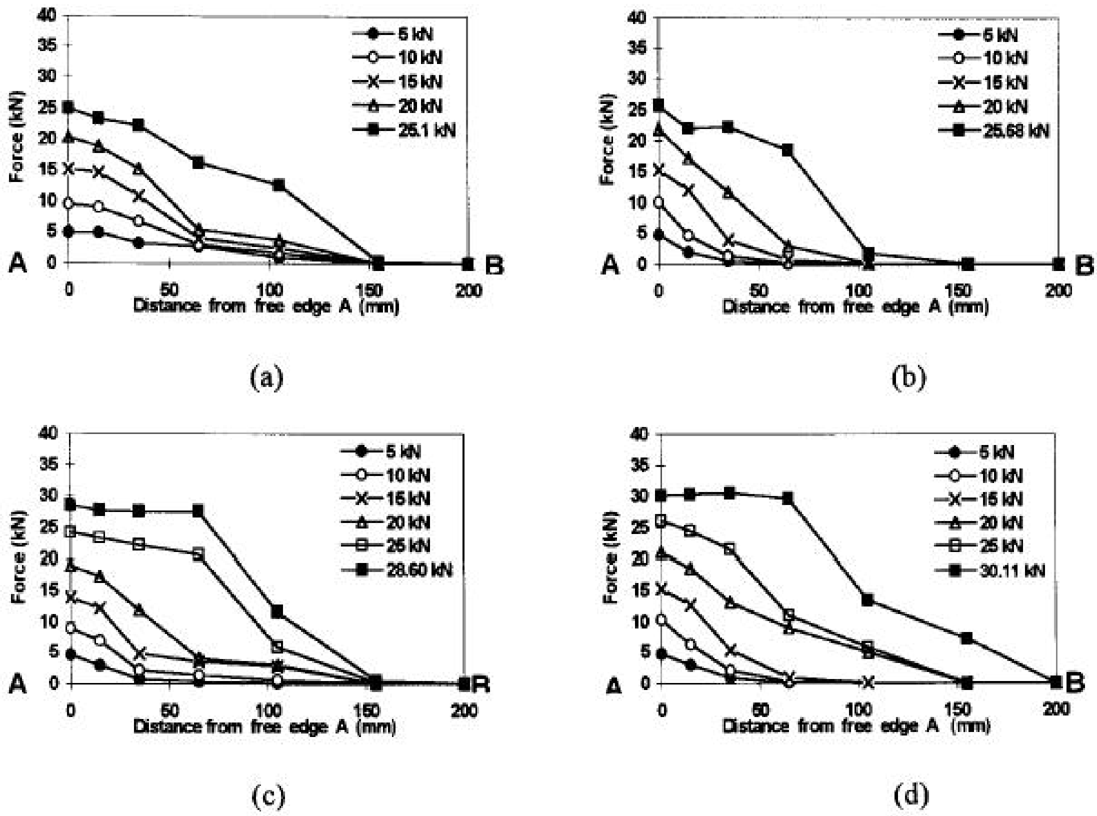


Fig. 2.9: Typical force transfer distributions for concrete mix B: (a) control; (b) wet/dry; (c) freeze/thaw; and (d) dual [10]

2.2.6 Failure Modes of Fibre Reinforced Polymer-Concrete Bonded System

Externally FRP bonded to concrete beams could fail in several ways when loaded in bending. If both reinforcing steel and FRP cross sectional area fractions are small, reinforcing steel yielding may be followed by rupture of FRP composite sheet or debonding of FRP plate. If the FRP cross sectional area fraction is high, failure is due to concrete crushing while the steel may have yielded or not, depending on its cross sectional area fraction. Debonding of FRP from concrete cover may occur due to the following phenomena [26-29];

i. The sudden propagation of cracks in the adhesive-concrete interface (i.e. due to brittleness of both materials).
ii. Peeling-off of the FRP sheet/plate due to opening caused by shear cracks in the concrete as shown in Fig. 2.10.

iii. Shear failure between concrete cover and FRP sheet layer and the longitudinal reinforcement.

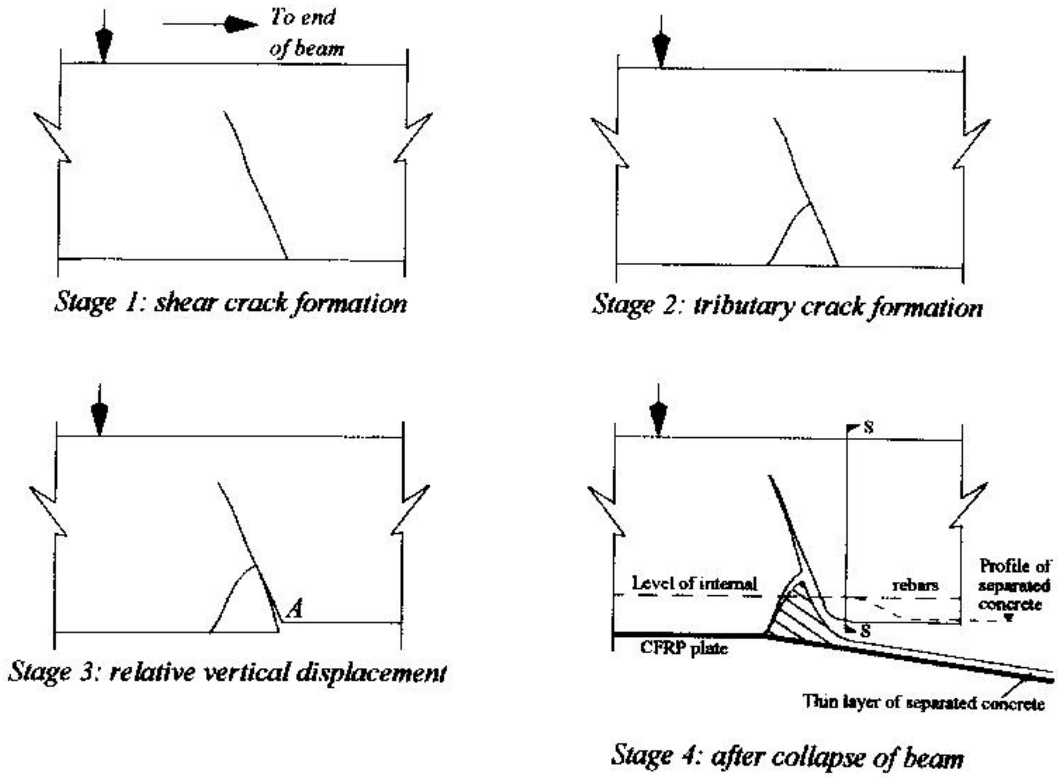


Fig. 2.10: Progressive failure of CFRP plate externally bonded to concrete due to vertical and horizontal concrete crack openings near to loading point [29]

Sheppard *et al.* [30] in their study on developing damaged zone model for adhesive bonded joint listed four types of failure modes by which an adhesive bonded joint could fail. The four primary failure modes are summarized as follows;

i. Adhesive failure that means a rupture of an adhesive bond, such that the separation is at the adhesive-adherend interface. This failure is mainly due to a material mismatch or inadequate surface treatment.

ii. Cohesive failure of adhesive means that when the adhesive fails due to loads exceeding the adhesive strength.

iii. Cohesive failure of adherend means that when the adherend fails due to loads in excess of the adherend strength, for example due to bending, tension or compression.

iv. Out-of plane adherend failure (this failure mode only occurs for composite adherends and is in form of intra-laminar and/or inter-laminar failure in adherends.

By referring to Mukhopadhyaya *et al.* [10], the failure of FRP plate-adhesive-concrete bonded subjected to tension-compression loads could occur in three different ways, namely; (a) cohesive failure in the adhesive layer, (b) adhesion failure and (c) concrete shearing failure. Those types of failure are shown in Fig. 2.11 (a) to Fig. 2.11 (c).

2.2.6.1 Failure at Interface

This may arise through failure of an interlayer between the substrate material and adhesive (i.e. an oxide coating or primer layer) or through failure of the adhesive bond surface. In practice, the interface is not perfectly flat and the surface topography acts to create a layer where there are both adhesive and substrate present.

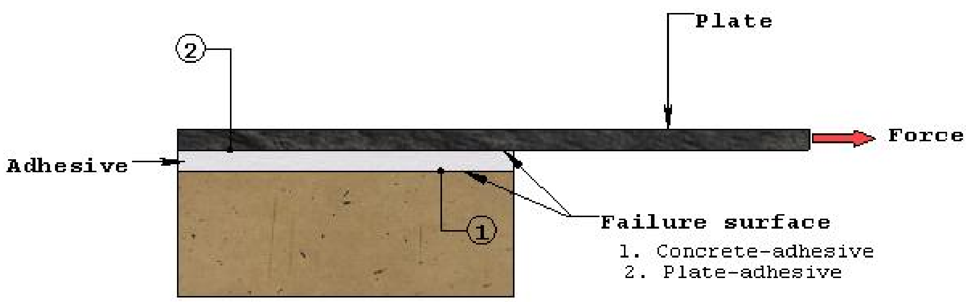


Fig. 2.11 (a): Cohesive failure

2.2.6.2 Adhesive Failure

Cohesive failure occurs through excessive strain with the adhesive material and may occur anywhere within the adhesive layer. Stresses and strains peak at the ends of the overlap and generally close to substrate.

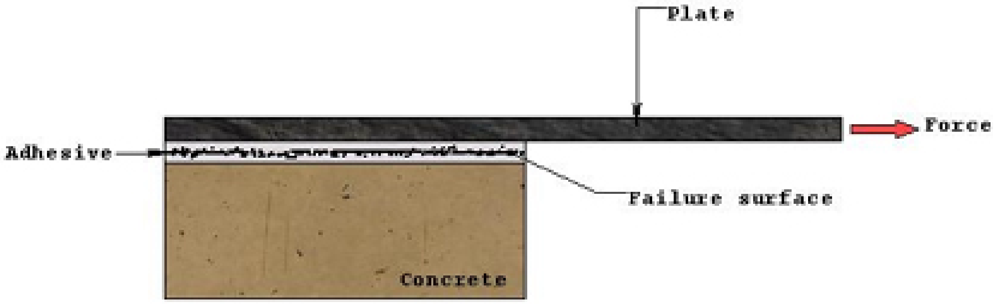


Fig. 2.11 (b): Adhesive failure

2.2.6.3 Adherend Failure

This type of failure will arise through development of excessive strain within the adherend material and it is more common to occur for brittle type materials. In particular, joints made with adherends of FRP composite with concrete bonded with toughened adhesive fail by adherend failure, usually by concrete shearing.

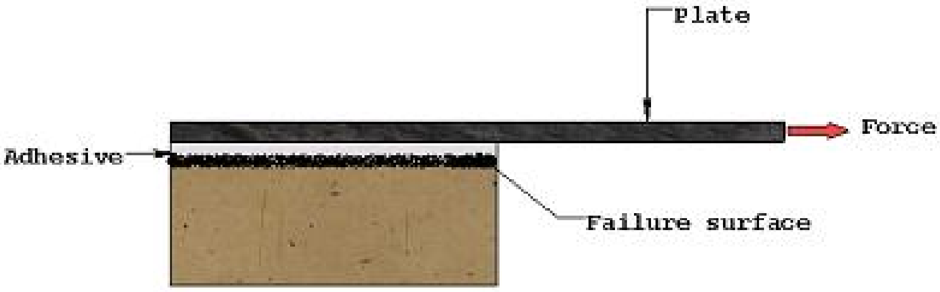


Fig. 2.11 (c): Adherend failure, i.e. concrete shearing

2.3 Weather Climatic Condition

The depletion of the stratospheric ozone layer, climate change, atmospheric acidification, desertification, loss of biodiversity and marine pollution are environmental issues of major concern reflecting the increasing influence of human activities on our fragile ecosystem. This is because their impacts and damages affect not only the countries where the problems originate, but also go beyond political boundaries and can reach global scale.

Many of these problems are interrelated in a very complex manner. For instance, burning of fossil fuels emits carbon dioxide that contributes to global warming. At the same time it also releases gaseous sulphur dioxide and nitrogen oxides into the atmosphere that are major precursors of acid deposition. These problems may lead to soil degradation, threaten wildlife and damage infrastructures.

This literature review is conducted to provide a clear scenario of the weather pattern and characteristic particularly in Malaysia especially to identify the factors that may contribute or relate to the research finding. This is important because the research conducted is related to the study of the effect of natural weather, i.e. tropical environmental conditions on the exposed specimens' mechanical performances [31].

2.3.1 Environmental Condition Definition

Radioactive flux determines the conditions under which materials function and degrade. The effect of temperature on degradation rate must also be considered since heat is another form of energy which acts simultaneously on materials. The composition of the atmosphere, including the moisture component, affects radioactive flux but moisture, in particular, and other atmospheric components initiate changes, often corrosive in exposed materials. Winds contribute to the transportation of matter and thus to the residence time of pollutants in the atmosphere and climate formation. Winds also affect temperature distribution on specimens during exposure periods. Clouds not only produce precipitation but also absorb sun radiation and reflect or absorb re-radiated energy. Lighting produces energy utilized for chemical reactions in the atmosphere. All of these, due to general circulation and transport processes, contribute to the climatic or environmental conditions which will affect the exposed material. The following analysis outlines important features and relations of these environmental conditions.

2.3.2 Effects of Ultraviolet Radiation

In recent years**,** Chin *et al.* [32] found that examined organic polymers and their composites have become increasingly important in outdoor applications. One of the components of the outdoor environment that has been shown to be deleterious to organic materials is solar ultraviolet (UV) radiation. Ultraviolet radiation that reaches the earth's surface comprises about 6% of the total solar radiant flux and has wavelengths between 290 nm and 400 nm. Radiation below approximately 290 nm is effectively eliminated by stratospheric ozone. The remainder of the solar radiation is composed of visible (52%) and infrared (42%) radiation. Since most polymers have bond dissociation energies of the order of 290 to 400 nm wavelengths in the ultraviolet region, they are greatly affected by exposure to this portion of the solar spectrum.

They [30] also emphasized that the chemical changes induced by UV exposure are the result of a complex set of processes involving the combined effect of UV and oxygen. Bond dissociation is initiated by the absorption of UV radiation, resulting in chain scission and/or cross linking; subsequent reactions with oxygen result in the formation of functional groups such as carbonyl (C=O), carboxyl (COOH), or peroxide (O-O). The effects of UV exposure or photo degradation are usually confined to the top few microns of the surface. However, in some cases, degradation at the surface of a polymeric component has been shown to affect mechanical properties disproportionately, as flaws that result from surface photo degradation can serve as stress concentrators and initiate fracture at stress levels much lower than those for unexposed specimens. The effect of ultraviolet radiation is also compounded by the action of temperature, moisture, wind-borne abrasives and other environmental components.

2.3.3 Temperature and Moisture

The surface temperature of materials is greatly affected by the absorption of radiant energy. Material type and colour determine the surface temperature. The rate of heat penetration depends on the thermal diffusivity of the material, on its heat capacity, and on its thermal conductivity. All three factors will determine the surface temperature. Absorption of solar radiation depends on the surface finish. A polished surface reflects more radiation than unpolished surface. Lighter coloured materials reflect more than darker one. In addition, wind speed has considerable effect on surface temperature increasing the rate of heat exchange. Humidity and the amount of precipitation are more local than global climatic phenomena and are classified as important factors in weathering studies.

2.3.4 Acid Deposition

The history of acidification began several hundred million years ago. At that time there were died plants and animals that over time were transformed into other form of material known as fossil fuels; coal, oil and natural gas. In addition to that, the burning oil and coal from boilers in factories and power plants or burning the fuel in automobiles, will release into the atmosphere millions of tons of sulphur and nitrogen in the form of sulphur dioxide and nitrogen oxides. These pollutants can be transported over long distances by the wind, undergoing chemical transformation to form sulphuric and nitric acids which return to the ground as acid deposition.

Acid deposition describes a process that is a combination of wet and dry deposition. Wet acidic deposition is also referred to as acid rain. Referring to Malaysia Meteorological Service [31], in the tropical region, acid rain accounts for only half of the total amount of acid that return to the earth; the other half is deposited in dry form.

In the wet deposition process, sulphuric and nitric acids are incorporated into cloud droplets during cloud formation. These rain drops will eventually fall onto the ground in the form of rain and snow. When high concentrations of acid are present, the rain shows strong acidity level.

Gaseous sulphur dioxide, nitrogen oxides and nitric acid, as well as acid aerosols are also deposited directly when they contact and adhere to the surface of vegetation, soil and other materials during fine weather. This process is known as dry deposition.

2.3.5 Rainwater Acidity

Acidity of a liquid is a measure of its hydrogen ion concentration. It is normally expressed in terms of a pH value. On a pH scale of 0 to 14, a pH value of less than 7 is acidic, pH value equal to 7 is neutral and a pH value greater than 7 is alkaline. Rainwater is naturally acidic due to the presence of carbon dioxide and other naturally produced acidic gases in our atmosphere. The pH of rainwater from very clean locations such as remote islands is found to have a value of between 5.6 and 6.0. Generally, rainwater with pH less than 5.6 is considered acidic. The pH of rainwater is measured either by using pH indicator strips and a pH colour chart, or by using a pH meter. Although pH is an important indicator of acidity, the relationship between pH value and acid concentration is rather complex as it is not linear.

2.4 Global Warming Issue and Weather Pattern in Malaysia

Generally, Malaysia is a humid tropical country and its climate is characterised by maritime monsoon winds which produce a uniform temperature, high humidity and heavy rainfall. Winds are generally light. Located at the equatorial doldrums area, it is extremely rare to have a full day with completely clear sky even in periods of severe drought [31].

Like most of the world, Malaysia also cannot run from the global warming or "climatic changes" effects. This environmental threat can produce serious economic losses to the society in various sectors and the nation as a whole. Nowadays, the global warming issue has become among the hottest topic spoken in academic forums around the world. The occurrence of "climate change" around the globe mainly is attributable to human activities that alters the atmospheric compositions. There are many factors identified as the cause of climate change, and can be categorised as local or global factors. Open burning (haze) is one of the global factors of which the effect is trans-border; while clearing land for agriculture that fragiles the ecosystem is an example of localised factor.

In recent years, attention on climate change has been targeted at global warming effects of atmospheric concentration of the greenhouse gases (i.e. CO_2) which have increased markedly from about 280 to 379 ppm over the last 650,000 years and 180 to 300 ppm as a result of human activities since 1750 [33].

In the context of global warming, extreme weather and climate events including longer droughts and heavy floods have been observed over wider areas since the 1970's, particularly in the tropics and subtropics regions [33]. The extreme weather climatic changes have resulted in climate related hazards such as landslides, flash-floods, localised storms and flooding. This global climate change has its likely impact on water resources, ecosystems, food production, coastal systems, industry, settlement, society and health, and on infrastructures such as road pavements and slopes and bridges. Additionally, an increase in the frequency and intensity of extreme climatic events, has brought about temperature extremes, storms, floods, and droughts. It increases in vulnerability as underlying risk factors which are compounded by climate-change-specific hazards, such as sea-level rise and glacier melt [34].

Natural disasters such as floods and landslides are common in Malaysia, as well as in many countries in this region. The warming effect in Siberia is the example that leads to a heavy rainfall in Southern Malaysia that produced a major flood that hit Malaysia twice. The first wave in December 2006 and the second wave in January 2007, resulted in flooding to six Peninsular states, including Sabah in East Malaysia. Among the most affected areas were Johor and southern Pahang. Districts such as Batu Pahat, Johor Bahru, Kluang, Kota Tinggi, Mersing, Muar, Pontian, Segamat and Rompin in Pahang were badly devastated, which resulted in economic standstill until the end of March 2007. It was reported that the warming effect in Siberia led to a heavy rainfall in Southern Malaysia.

The effects of damages are in the form of pavement potholes, surface delaminating, landslides, and scouring at bridge embankments, culverts and river banks. An estimated cost of RM 320 million (USD 90 million) were required to revive the economy and to rehabilitate the infrastructure pavements, bridges and slopes [34].

2.4.1 Rainfall Distribution

The seasonal wind flow patterns coupled with the local topographic features determine the rainfall distribution patterns over the country. During the northeast monsoon season, the exposed areas like the east coast of Peninsular Malaysia, Western Sarawak and the northeast coast of Sabah experience heavy rain spells. On the other hand, inland areas or areas which are sheltered by mountain ranges are relatively free from its influence. The rainfall distribution pattern in Peninsular Malaysia for the year 2002 can best be referred to in Fig. 2.12.

2.4.1.1 Seasonal Rainfall Variation in Peninsular Malaysia

Referring to the Malaysian Meteorological Service, the seasonal variation of rainfall in Peninsular Malaysia can be classified into three main types;

i. Over the east coast districts, November, December and January are the months with maximum rainfall, while June and July are the driest months in most districts.

ii. Over the rest of the Peninsular with the exception of the southwest coastal area, the monthly rainfall shows a pattern of two cyclic periods of maximum rainfall which are separated by two periods of minimum rainfall. The primary maximum generally occurs in October to November while the secondary cycle occurs in April to May. Over the north-western region, the primary minimum occurs in January to February with the secondary minimum in June to July, while elsewhere the primary minimum occurs in June to July with the secondary minimum in February.

iii. The rainfall pattern over the southwest coastal area is much affected by early morning "Sumatras" from May to August with the result that the double maximum and minimum pattern is no longer discernible. October and November are the months with maximum rainfall, whereas February is the month with minimum rainfall. The March, April and May maximum and the June and July minimum are absent or indistinct.

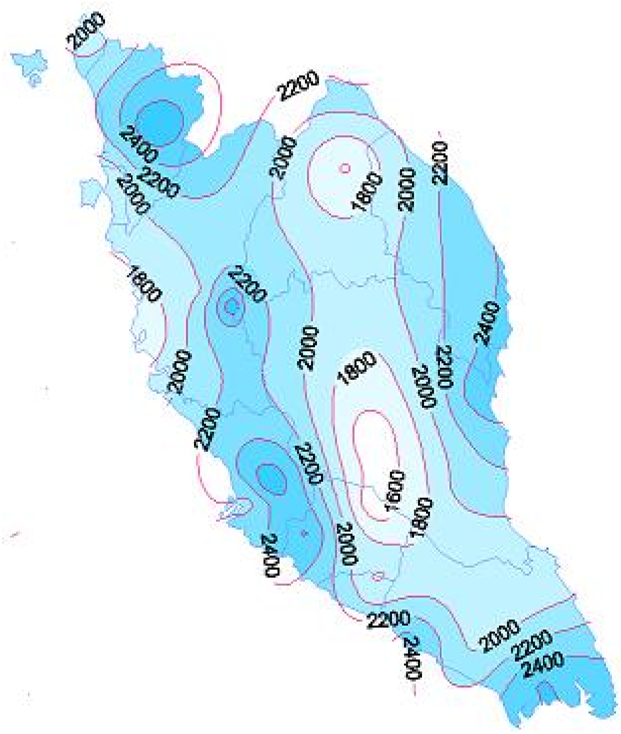


Fig. 2.12: The 2002 annual rainfall (mm) distribution patterns for Peninsular Malaysia [31]

2.4.2 Temperature Distribution

Being an equatorial country, Malaysia has uniform temperature throughout the year. The annual variation is less than 2°C except for the east coast areas of Peninsular Malaysia which are often affected by cold surges originating from Siberia during the northeast monsoon. Even there, the annual variation is below 3°C. The temperature distribution in the Peninsular of Malaysia in the form of mean, minimum and maximum for the year 2002 can best be referred to in Fig. 2.13.

The daily range of temperature difference is relatively large, being from 5 to 10°C at the coastal stations and from 8 to 12°C at the inland stations, but excessive day temperatures which are found in continental tropical areas have never been experienced. It may be noted that air temperature of 38°C has very rarely been recorded in Malaysia. Although the days are frequently hot, the nights are reasonably cool elsewhere.

Although the seasonal and spatial temperature variations are relatively small, they are nevertheless fairly definite in some respects and are worthy to mention. Over the whole Peninsular, there is a definite variation of temperature with the monsoons and this is accentuated in the east coast districts. April and May are the months with the highest average monthly temperature in most places. On the other hand, December and January are the months with the lowest average monthly temperature. The average daily temperature in most districts to the east of the Main Range is lower than that of the corresponding districts west of the Main Range. The differences in the average values in the east and the west are due almost entirely to the low day temperatures experienced in the eastern districts during the northeast monsoon as a result of rain and greater cloud cover. In Kuala Terengganu, for example, the day temperature rarely reaches 32°C during the northeast monsoon and often fails to reach 27°C. A number of occasions have been recorded in which the temperature did not rise above 24°C which is quite frequently the lowest temperature reached during the night in most districts. Night temperatures do not vary to the same extent, the average usually being between 21 to 24°C. Individual values can fall much below this at nearly all stations, the coolest nights commonly follow some of the hottest days.

Fig. 2.13: The 2002 annual 24-hour mean, mean maximum and mean minimum temperature deviation patterns [31]

2.4.3 Relative Humidity

As mentioned earlier, Malaysia has a high humidity. The monthly mean relative humidity falls within 70 to 90%, varying from place to place and from month to month. For any specific area, the range of the mean monthly relative humidity varies from a minimum of 3% to a maximum of about 15%. In Peninsular Malaysia, the minimum range of mean relative humidity varies from a low of 84% in February to a high of 88% in November. The maximum range is found in the northwest area of the Peninsular (Alor Setar) where the mean relative humidity varies from a low of 72% in February to a high of 87%. It is observed that in Peninsular Malaysia, the minimum relative humidity is normally found in the months of January and February except for the east coast states of Kelantan and Terengganu which have the minimum in March. The maximum is however generally found in the month of November. As in the case of temperature, the diurnal variation of relative humidity is much greater as compared to the annual variation. The mean daily minimum can be as low as 42% during the dry months and reaches as high as 70% during the wet months. The mean daily maximum, however, does not vary much from place to place and is at no place falls below 94%. It may reach as high as nearly 100%. Again, the northwest states of Kedah and Perlis have the largest diurnal variation of relative humidity.

2.4.4 Sunshine and Solar Radiation

Being a maritime country close to the equator, Malaysia naturally has abundant sunshine and thus solar radiation. However, it is extremely rare to have a full day with completely clear sky even in periods of severe drought. The cloud cover cuts off a substantial amount of sunshine and thus solar radiation. On the average, Malaysia receives about 6 hours of sunshine per day. There are, however, seasonal and spatial variations in the amount of sunshine received. Alor Setar and Kota Bharu receive about 7 hours per day of sunshine while Kuching receives only 5 hours on the average. On the extreme, Kuching receives only an average of 3.7 hours per day in the month of January. On the other end of the scale, Alor Setar receives a maximum of 8.7 hours per day on the average in the same month. Solar radiation is closely related to the sunshine duration. Its seasonal and spatial variations are thus very much the same as in the case of sunshine.

2.4.5 Evaporation

Among the factors affecting the rate of evaporation are cloudiness and temperature, which are the most important ones in this country. These two factors are however inter-related. A cloudy day will mean less sunshine and thus less solar radiation and in turn results in lower temperature.

An examination of the evaporation data shows that the cloudy or rainy months are the months with lower evaporation rate while the dry months are the months with higher rate. It is noted that Senai has an average evaporation rate of 2.6 mm/day in the month of November, the lowest for lowland stations. On the other end of the scale, Kota Kinabalu has the highest average evaporation rate of 6.0 mm/day in the month of April. For highland areas such as in Cameron Highlands (i.e. in the state of Pahang) where the air temperature is substantially lower, the evaporation rate is proportionally lower. While lowland areas have an annual average evaporation rate of 4 to 5 mm/day, Cameron Highlands has a rate of only about 2.5 mm/day.

2.4.6 Rainfall Acidity

From Fig. 2.14, it can be seen that the northern and western states of Peninsular Malaysia receive rainfall with pH between 4.8 and 5.2, while the other parts of the peninsula receive rainfall with pH between 4.4 and 4.8. The areas that experience high levels of acidity are located in and around the Klang Valley (Kuala Lumpur) and southern part of Johor state. Coincidently, these areas are rapid growth centres with heavily industrialised as well as high population density. The main factor that contributes to the high acidity level in the southern region is due to increasing number of motor vehicles apart from the development in industrialised sector. It is suspected that the pH value in the most critical areas remains or is getting worse due to lack of enforcement.

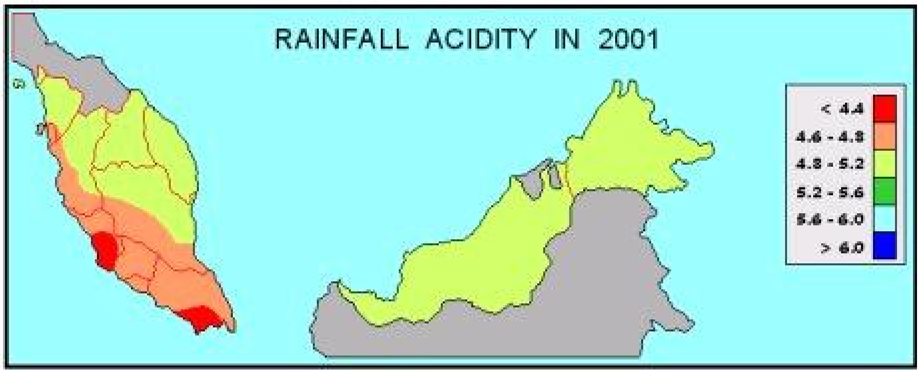


Fig. 2.14: Rainfall acidity in Malaysia for the year of 2001 [31]

2.5 Senai Meteorological Service Station Climatic Data

The state of Johor Meteorological Service Station is located about 18 km from UTM main campus. The recorded weathering data by the station are assumed to be equivalent to the experimentation site that has been set up in UTM campus.

2.5.1 Relative Humidity

Fig. 2.15 shows the graph of Mean Relative Humidity for 26 years in the form of histogram that was collected by the Senai Meteorological Service Station from 1975 to 2004 [31].

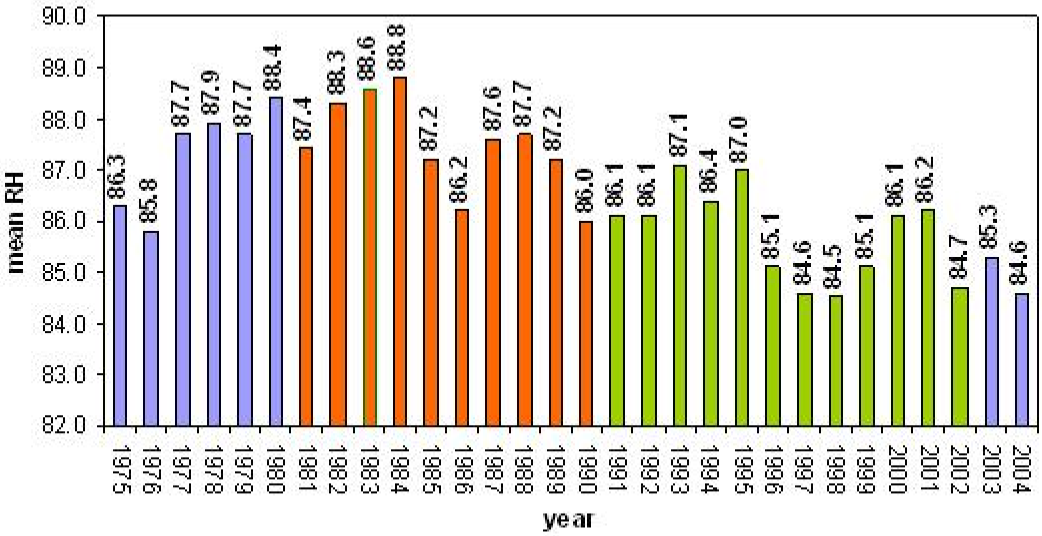


Fig. 2.15: Annual Mean Relative Humidity in Senai Meteorological Service Station

Relative humidity spreads throughout the Malaysian Peninsula. In the context of data referred to Senai Meteorological Service Station, the mean monthly relative humidity falls within the 80 to 90% annually. On average, the annual mean relative humidity for Senai recorded from 1974 to 2004 was about 84.5 to 88.8%. This averaged about 86.7% for the mentioned period. In between the year of 1974 to 2004, year 1984 produced the highest mean relative humidity while year 1998 was the lowest. An obvious pattern of a decrease in the mean relative humidity could be seen post 1984 where the annual mean relative humidity fell gradually until it reached its lowest point in year 1998. Prior reaching its peak in 1984, the average annual mean relative humidity was about 87.6% and after year 1984, the average mean relative humidity was around 87.0%, and around 85.4% after year 1998. This illustrated that the pattern of rainfall in Senai experienced a gradual decrease from the 1970's up to the 21st century.

2.5.2 Wet Fallouts

Based on the Wet Fallouts 1993-2004 data, the analysis of the results depicted several findings that could determine the trend of rainfall in Senai. From sixteen minerals contained in the rainfall there are seven main minerals that dominate the rain content in Senai (Table 2.3). In addition, there is a slight increase in mineral rain contents which are manganese and lead. The annual average mineral content in rainfall is shown in Figs. 2.18 (a) to (g). From the figures, it can be seen that the mineral rain content such as chloride, sodium, nitrate, potassium, ammonium and sulfate were recorded among the highest density increment since 1993. In terms of percentage increment, chloride was the highest mineral content recorded in year 2003 and year 2004, which was in range of 2800 to 3000% increment compared to the averaged annual data from year 1993 to 2002. These followed by sodium and nitrate, which were about 2500 to 2700% and 800 to 1300%.

The mineral content increment from year 2003 is very significant in terms of pollution index in the area of Senai or Johor Bahru as a whole. The description that was mentioned in section 2.3.7 supports the results together with graphs in Fig. 2.17 and 2.18. The most probable factor of the large increment was the fast economic development in southern part of Johor part since 1990's resulting in the increment of the number of motor vehicles on the roads that could be related to the increment of sulfur dioxide gas to the atmosphere.

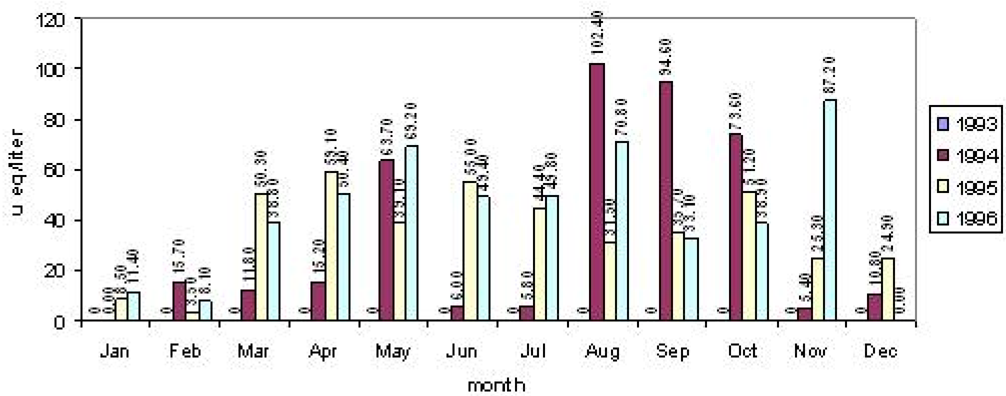


Fig. 2.16: Acidity rainfall measured at Senai Meteorological Station from year 1993 to 1996

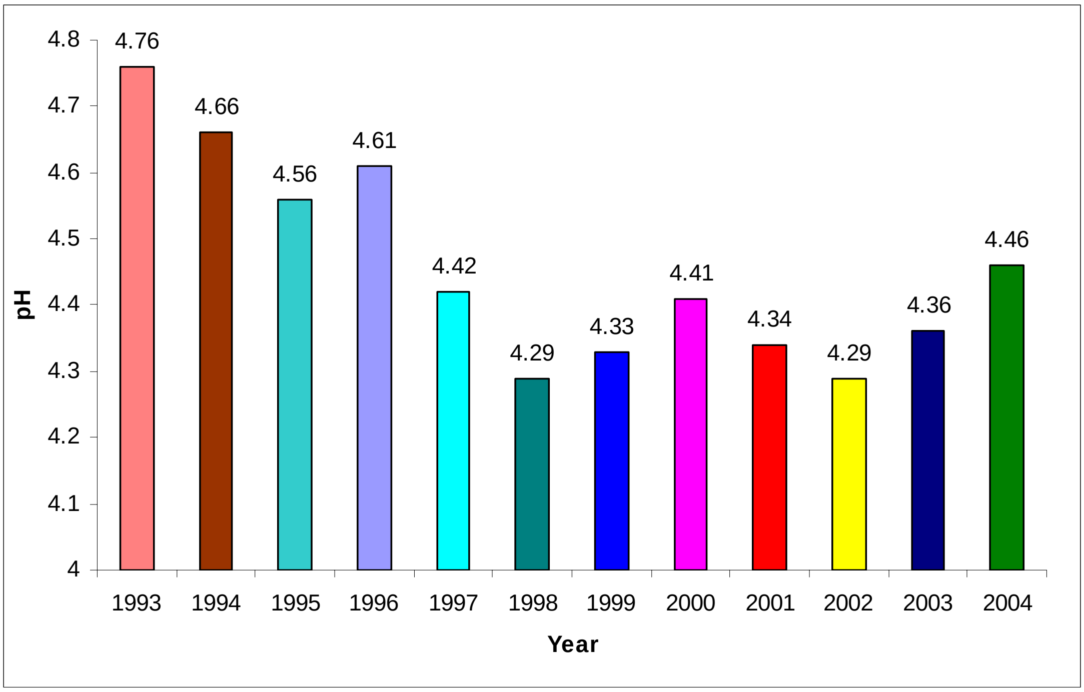


Fig. 2.17: pH of rainfall measured at Senai Meteorological Station from year 1993 to 2004

Table 2.3: The mineral rain content recorded data by Senai Meteorological Service Station

Mineral/Density	Minimum 1993 to 2002 (mg/litre)	Maximum 1993 to 2002 (mg/litre)	Average 1993 to 2002 (mg/litre)	2003 (mg/litre)	Increment (%)	2004 (mg/litre)	Increment (%)
Sodium	0.2	1.02	0.435	12.08	2677	11.12	2456
Potassium	0.07	0.32	0.161	1.74	980.	2.26	1303
Ammonium	0.12	0.81	0.337	3.02	796	2.30	582
Calcium	0.14	0.47	0.235	4.65	1837	6.27	2512
Nitrate	0.14	0.51	0.275	4.10	1390	2.58	838
Sulfate	0.3	1.08	0.785	6.79	765	7.13	808
Cloride	0.37	0.75	0.539	16.71	3000	15.61	2796

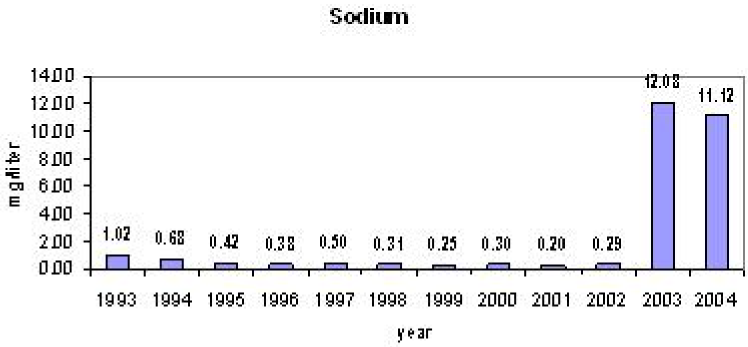


Fig. 2.18 (a): Sodium content in rainfall at Senai Station from year 1993 to 2004

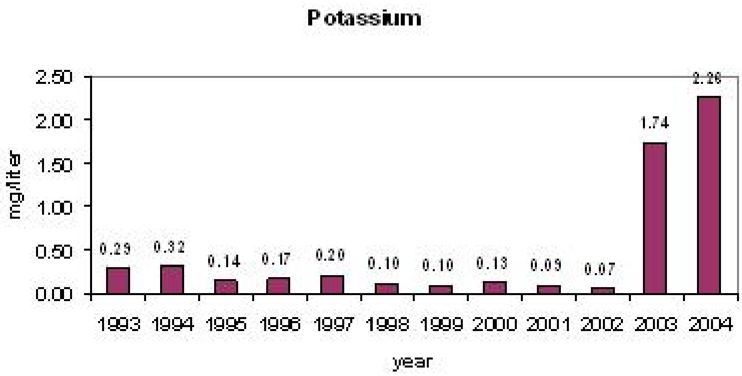


Fig. 2.18 (b): Potassium content in rainfall at Senai Station from year 1993 to 2004

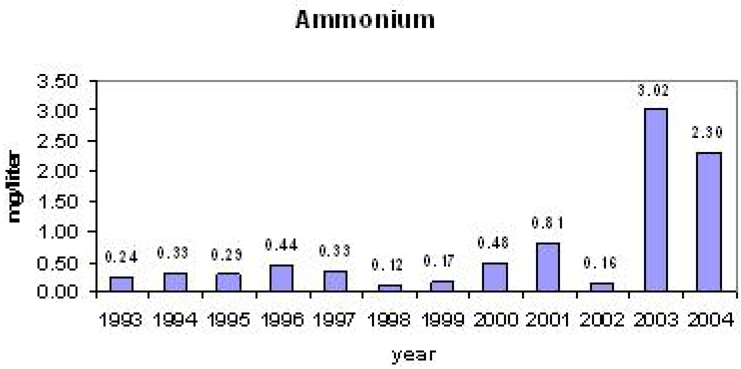


Fig 2.18 (c): Ammonium content in rainfall at Senai Station from year 1993 to 2004

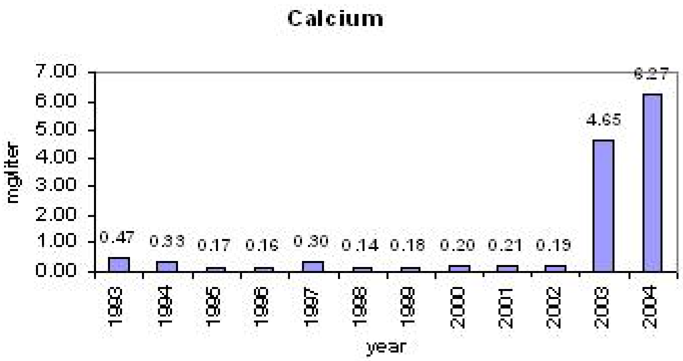


Fig. 2.18 (d): Calcium content in rainfall at Senai Station from year 1993 to 2004

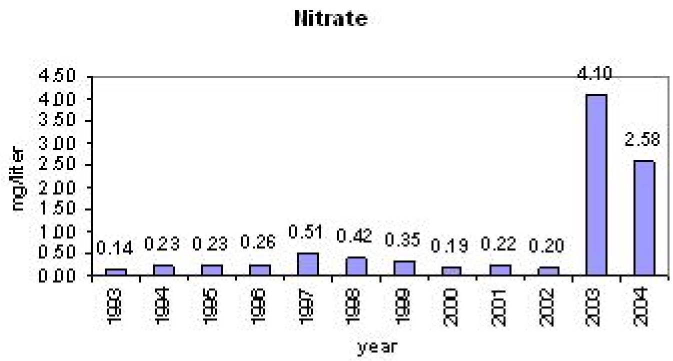


Fig. 2.18 (e): Nitrate content in rainfall at Senai Station from year 1993 to 2004

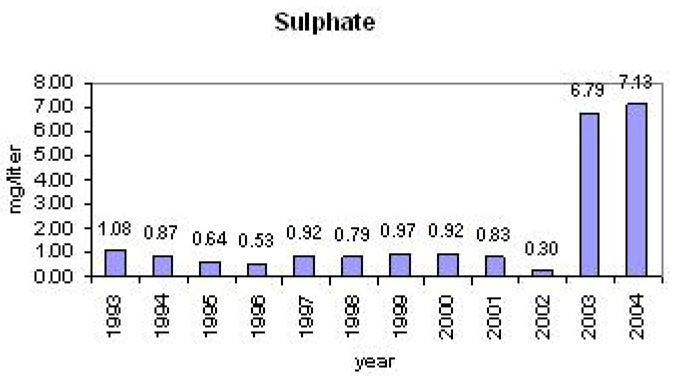


Fig. 2.18 (f): Sulphate content in rainfall at Senai Station from year 1993 to 2004

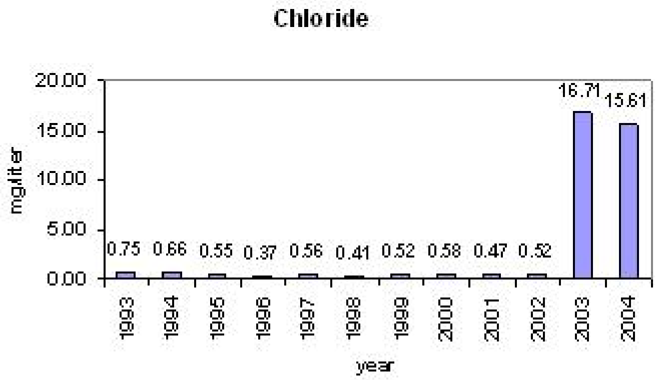


Fig. 2.18 (g): Chloride content in rainfall at Senai Station from year 1993 to 2004

2.5.3 Temperature Distribution

By referring to the recorded data provided by Senai Meteorological Service Station from 1975 to 2004, it can be seen that the temperature distribution was almost constant throughout the years as it hit between 21.7ºC and 32.8ºC. For example, the mean temperature read out an average of 26.0ºC, with the highest temperature of 27.1ºC and lowest was at 25.3ºC. Furthermore, the average mean maximum temperature was 31.8ºC with the highest and lowest temperatures were at 32.8ºC and 31.1ºC respectively. In addition, the mean minimum temperature averaged about 22.6ºC where the highest was 23.6ºC and 21.7ºC was the lowest. The temperature distribution around Senai areas is shown in Figs. 2.19 (a) to (e).

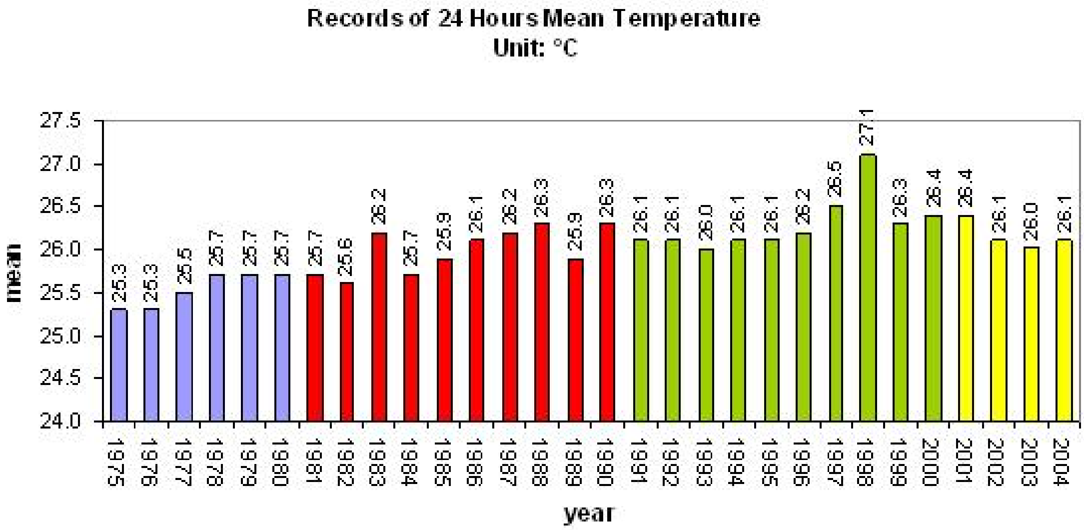


Fig. 2.19 (a): Mean Temperature at Senai Meteorological Service Station from year 1975 to 2004 [31]

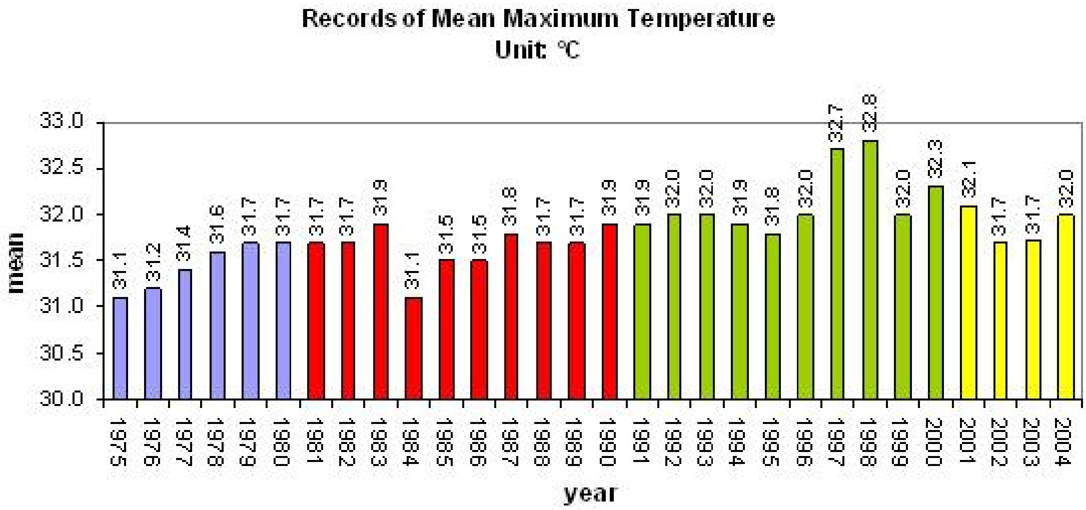


Fig. 2.19 (b): Mean Maximum Temperature in Senai Meteorological Service Station from year 1975 to 2004 [31]

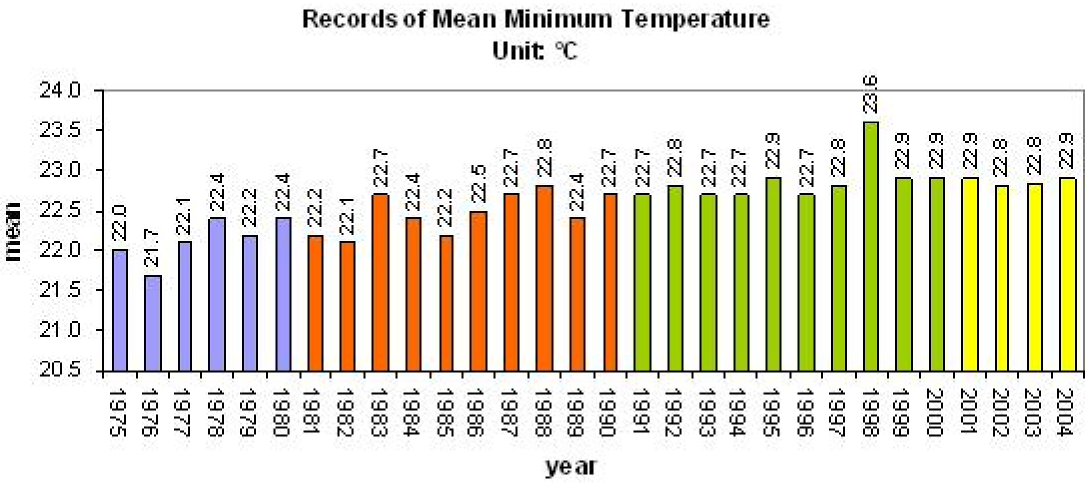


Fig. 2.19 (c): Mean Minimum Temperature in Senai Meteorological Service Station from year 1975 to 2004 [31]

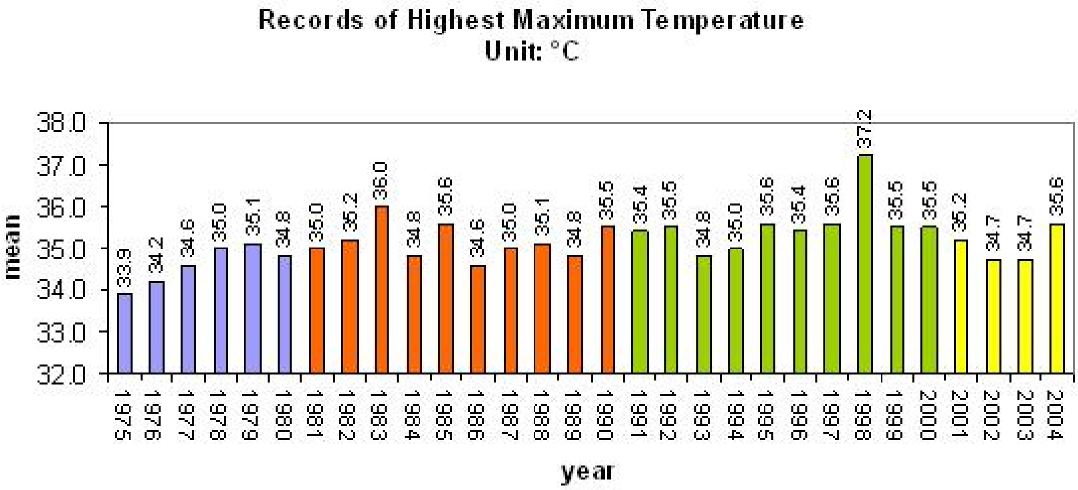


Fig. 2.19 (d): Highest Maximum Temperature at Senai Meteorological Service Station from year 1975 to 2004 [31]

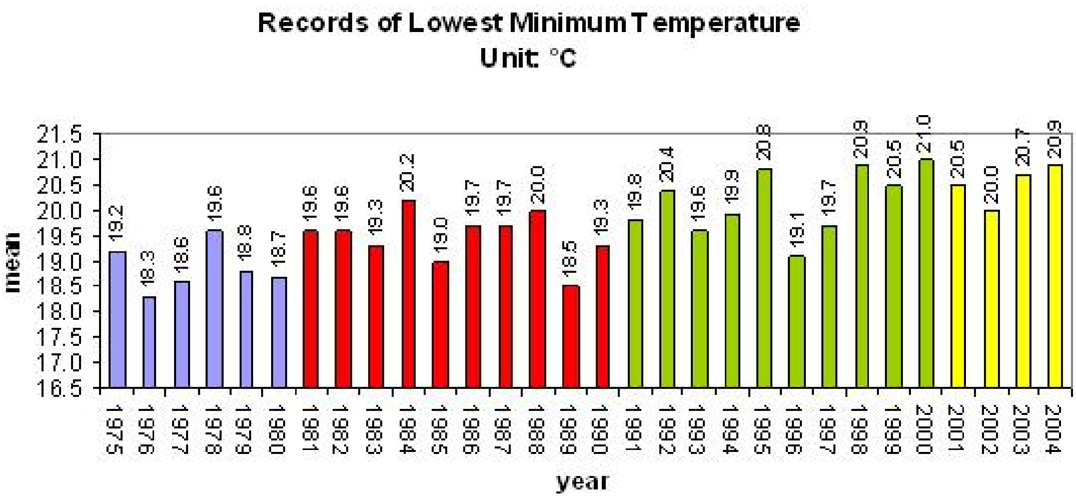


Fig. 2.19 (e): The Lowest Maximum Temperature at Senai Meteorological Service Station from year 1975 to 2004 [31]

2.6 Fibre Reinforced Polymer Composites

Composite material can be defined as a material that consists of multiphase material that exhibits a proportion of the properties of both constituent phases such that a better combination of properties can be produced. Traditionally, a composite material can be modelled as a material that consists of a matrix phase and a reinforcement phase, with the overall quality and efficiency of the material being primarily determined by the efficiency of the load transfer mechanisms. Advanced composite materials are classified as materials that possess high strength, high modulus to weight ratio and high fracture toughness whilst not exhibiting an increase in weight.

2.6.1 Load Bearing Advanced Fibre Reinforced Polymer Composites Structure

Fibre Reinforced Polymer (FRP) composites have been successfully used in engineering structures for many years in the aerospace, automotive, marine, chemical industries, etc. FRP composite is more preferable than steel for such specific applications due to its durability aspects when exposed to extreme environmental conditions such as polluted or coastal area, high temperature fluctuation and high moisture condition.

The mechanical properties of three different classes of Carbon Fibre Reinforced Polymer (CFRP) plates produced through Pultrusion process which is classified as an advanced composite is shown in Table 2.4. The CFRP plates are categorized as follows; Type S referred to as high tensile strength, Type M referred to as high strength with intermediate modulus, and Type H known as high modulus composite. In the application of strengthening steel structure, type M is most preferred due to its compatibility to elastic properties of mild steel material. The three most popular reinforcing fibre systems that have been classified as advanced materials are shown in Table 2.5.

Table 2.4: Properties of Selfix Carbofibe Pultruded CFRP Plates System [35]

Plate type	Tensile strength (MPa)	Tensile modulus (GPa)	Plate width (mm)	Plate thickness (mm)
S	2800	150	50/80/120	1.2/1.4
M	3200	200	50/80/120	1.2/1.4
H	1600	280	50/80/120	1.2/1.4

Table 2.5: Typical reinforcing unidirectional fibre properties [36]

Fibre	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)	Specific density
Carbon: high strength* Carbon: high modulus* Carbon: ultra high modulus**	4300-4900 2740-5490 2600-4020	230-240 294-329 540-640	1.9-2.1 0.7-1.9 0.4-0.8	1.8 1.78-1.81 1.91-2.12
Aramid: high strength and high modulus	3200-3600	124-130	2.4	1.44
Glass	2400-3500	70-85	3.5-4.7	2.6

Notes: (*) - Polacrylonitrile (PAN) based precursor

(**) – Pitch based precursor

2.6.1.1 Carbon Fibre

Carbon fibres are currently the predominant high strength to high modulus fibres used in the manufacture of advanced polymer composites load bearing structures such as for automotive driveshaft, bridge beam, wings skin for jet fighter etc. The philosophy of carbon fibre production technology was to produce lightweight, stiff and strong materials for the rapidly growing aerospace industry. Typical sizes of carbon fibres are in between 6 μm and 8 μm in diameter and consist of small crystallites of turbo static graphite, i.e. one of the allotropic forms of carbon. The carbon fibres are formed by treating organic fibres (precursors) with heat and tension to form a highly ordered carbon structure.

2.6.2 The Pultrusion Processing Technique

Pultrusion [37] is a process that enables hybrid composite components in the forms of rod, profile sections, and tubular sections to be manufactured in continuous lengths. The basic technique employed is to impregnate the reinforcing fibres, in continuous form with resin matrix such as polyester or epoxy prior to pulling the impregnated fibres through a curing and post curing die zones which impart the desired shape to the composite. A diagrammatic representation of the process is shown in Fig. 2.20.

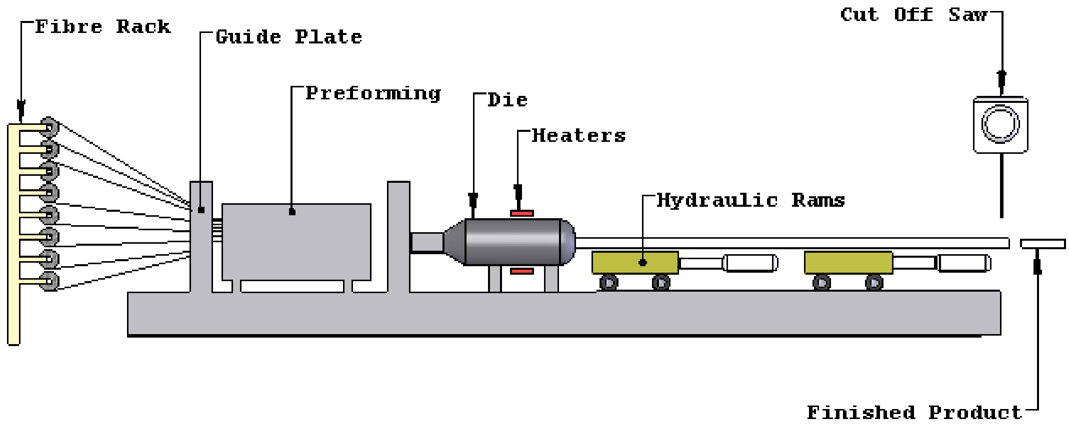


Fig. 2.20: The Pultrusion process in manufacturing FRP plate

Pultrusion machine is capable of producing hundreds of metres of profile section per hour under a single control operation. A wide range of component shapes can be manufactured by this process at a very competitive cost due to its highly automated nature (Fig. 2.21). Polyesters, vinyl esters and epoxy resins are among the principal matrix systems that have been used for the process coupled with carbon, glass, aramid or hybrid of these reinforcement materials respectively.

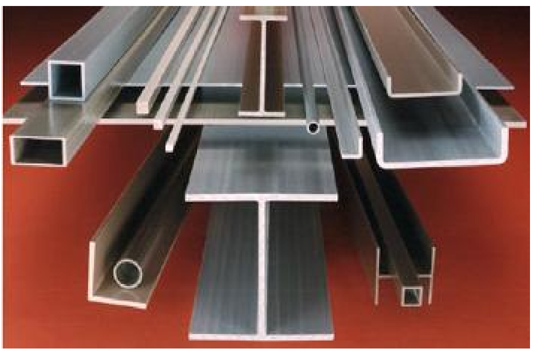


Fig. 2.21: Products produced by Pultrusion processing technique [38]

2.6.3 Fibre Reinforced Polymer Pultruded Composites Plate

One of the most important properties of FRP composites is the tensile behaviour, whereby the stiffness and strength of FRP composites can be varied in magnitude and direction to meet the structural design requirements. From experience in the testing fields, it can be seen that the mechanical properties of FRP under tensile load are greatly influenced by fibre properties, fibre forms, fibre volume fraction, fibre orientation, matrix properties and processing methods [39]. In design practice, the reinforcing fibres are specifically oriented parallel to the applied load in order to exploit the maximum strength of the fibres. The best example is orthotropic pultruded CFRP plate being used for upgrading the flexural performances of reinforced concrete structures (Fig. 2.22) [40-42].

Fig. 2.22: CFRP Plate (black strip) externally bonded to tension face of reinforced concrete beam [40]

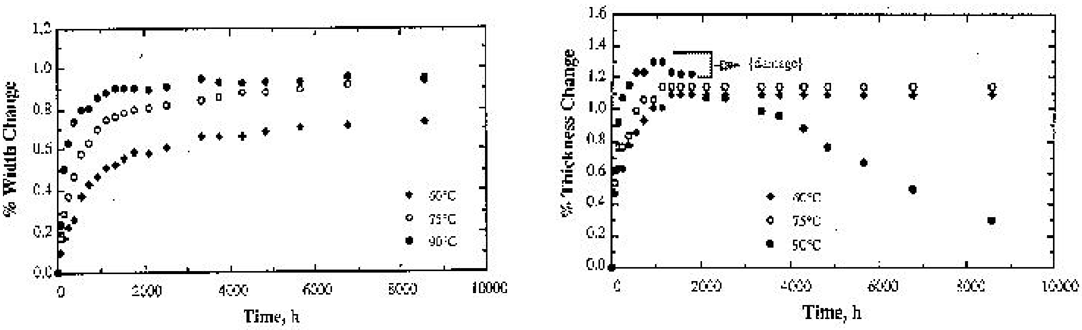
2.6.4 Durability of Fibre Reinforced Polymer Composites

More recently, the use of FRP composite materials was extended to be used as primary structures in aircrafts, automotive applications and infrastructure such as for rehabilitation or strengthening of steel or reinforced concrete bridges and buildings. This fact brings the issue of durability which the long-term experimentation results can be used to predict the properties and residual life, as a determinant factor in the success of the referred applications. FRP composite materials are found to increase in infrastructure applications, where design life cycles are about ten times longer than those in aerospace, the issue of durability becomes more critical and must be seriously taken into account.

The studies conducted by previous researchers on durability performances of FRP composites are the main focus of the following literatures review. The review is to gain knowledge related to the durability study of FRP composite effects from exposure to moisture environment conditions (i.e. outdoor, fresh water and salt water). Referring to the study conducted by Zhou and Lucas [43], on the effects of unidirectional graphite/epoxy composite under water environment at temperature of 45°C, 60°C, 75°C and 90°C exposed for more than 8000 hours. Two important factors were revealed and are summarised as follows;

i. Water sorption in graphite/epoxy (T300/934) material exhibited both Fickian and non-Fickian diffusion behaviour. The materials obeyed the Fickian diffusion behaviour at lower temperatures and non-Fickian behaviour at higher temperatures. The non-Fickian behaviour was resulted from chemical modification and physical damage to the epoxy resin. Cracks, voids and surface peeling were observed clearly through SEM and optical microscopy.

ii. Moisture-induced expansion of T300/934 composite was measured in length (fibre direction), width and thickness directions. There was no expansion due to water absorption detected in the fibre direction dimension. Significant dimensional changes resulting from moisture-induced expansion were observed in the width and thickness directions of the laminate. The decreased in thickness of the specimen at high temperature was associated to surface resin dissolution and peeling. These characteristics are shown in Figs. 2.23 (a), (b) and (c).



(a) (b)

Fig. 2.23 (a) and (b): The changes of width and thickness respectively of T300/934 graphite/epoxy immersed in distilled water at different temperatures [43]

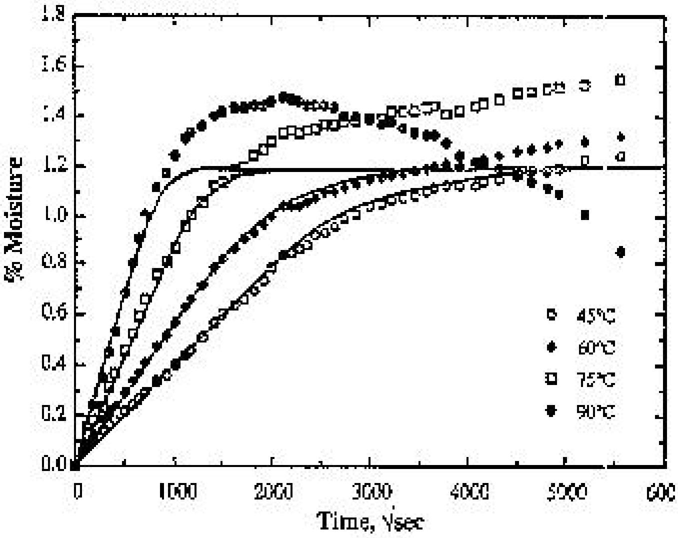


Fig. 2.23 (c): The weight change of T300/934 graphite/ epoxy immersed in distilled water at different temperatures. The solid lines represent theoretical Fickian diffusion [43]

Amer *et al.* [44], in their studies related to hydrothermal effect on single fibre composite had revealed that the interfacial degradation mechanism due to environmental exposure of graphite/epoxy was mechanical in nature. Matrix swelling was the main factor that degraded the interfacial stresses which finally produced a complex state of stress within the fibre-matrix interface. Their study also revealed that the analysis done on the single fibre system was able to predict the bulk composites behaviour. This was confirmed by experimental and FEA on bulk composites with volume fraction ranging from 63 to 71%.

Long-term durability study was conducted by Liaoa *et al.* [45] on pultruded glass-fibre-reinforced vinyl ester composite coupons subjected to various environmental conditions to study the long-term durability for infrastructure applications. Several groups of specimen were aged in water or in salt solutions containing mass fractions of 5% NaCl and 10% NaCl for up to 6570 hours. The control and experimented specimens were cyclically tested in air or while immersed in water or in salt solution. For specimens cyclically loaded at or above 45% of the average flexural strength of the dry coupons, no substantial difference in fatigue life was observed among all the specimen groups. For samples cyclically loaded at 30% of the dry flexural strength, however, all specimens tested in air survived beyond 107 cycles while all those tested in water environments did not. It was found that long-term environmental fatigue behaviour was not controlled by the quantity of water absorbed; rather, it was governed by a combination of both load and fluid environment. No difference in fatigue life was found for specimens exposed in different fluid environments at room temperature prior to fatigue testing. Relative to these samples, however, a significant difference was seen for specimens exposed in water at 75°C for 2400 hours prior to cyclic test at load levels above 30% of the dry flexural strength (Fig. 2.24). When tested at 30% of the dry flexural strength the differences were within the experimental uncertainty. Microscopic examination of the fatigue specimens revealed evidence of a degraded fibre-matrix interphase region in those specimens where environmental exposure caused premature failure so this was believed to be a controlling factor in the environmental performance of the glass composite.

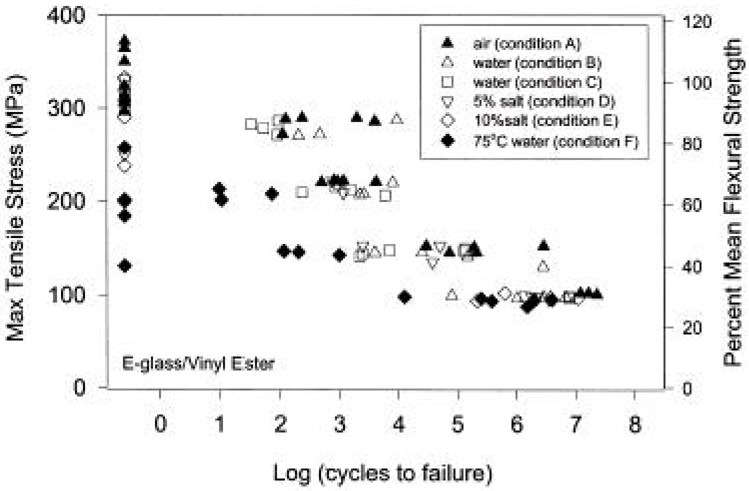
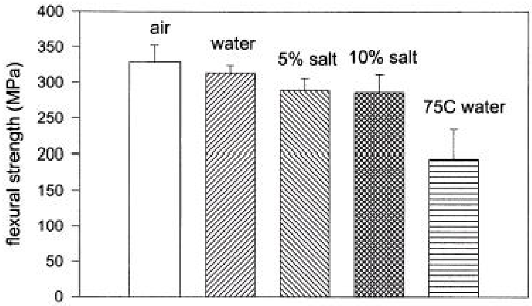


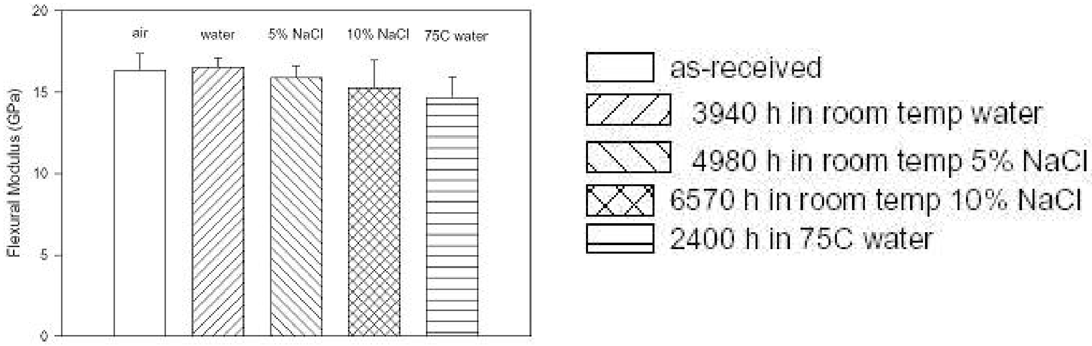
Fig. 2.24: Stress-life (S-N) data for pultruded composite coupons tested in fatigue at room temperature using environmental conditions A through to F [45]

Liaoa *et al.* [46], studied the durability of pultruded glass fibre reinforced vinyl ester matrix composite coupons subjected to environmental aging in water and salt solutions at room temperature of 25°C and in water at 75°C for various times. The flexural properties (strength and modulus) were determined for bending perpendicular to the 0º orientations for all aging conditions. In addition, flexural properties in the 90º orientation and tensile properties in the 0º orientation were also tested for the control specimens and the specimens exposed to the selected aging conditions. Both strengths and moduli were generally found to decrease with environmental aging. A group of specimens were also experimented in room temperature water for 9120 hours before being tested for failure in tension. The mean tensile modulus after aging (14.4 GPa) was 23% lower than that before aging (18.6 GPa). The mean tensile strength after aging (227 MPa) dropped by 29% compared to those without aging (160 MPa). The failure strain for the control and the aged specimens were 2.1% and 1.4%, respectively.

In addition, examination of the failure surfaces and comparisons between the strength of the 90º specimens suggested that the degradation of the fibre-matrix interphase region also occurred during the experimentation period. The durability study results were presented in the following respective graphs shown in Fig. 2.25 (a) and (b), Fig. 2.26 and Fig. 2.27.



(a)



(b)

Fig. 2.25 (a) and (b): Flexural strength and modulus for 0º specimens of pultruded composite coupons before and after environmental exposure [46]

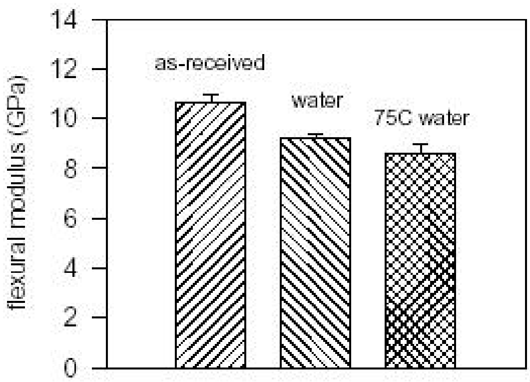


Fig. 2.26: Flexural modulus for 90° specimens of pultruded composite coupons before and after environmental exposure [46]

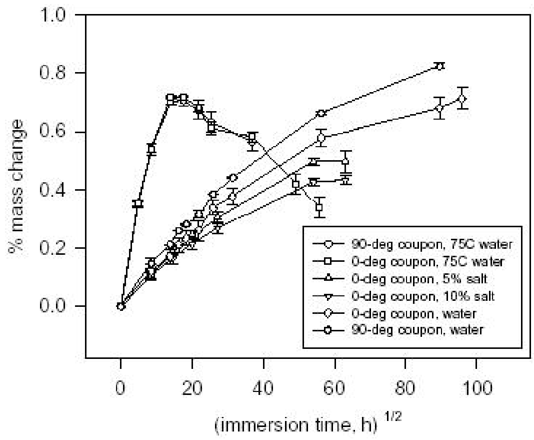


Fig. 2.27: Sorption behaviour of pultruded composite coupons under various exposure conditions [46]

The study conducted by McBagonluri *et al.* [47] on the effects of short-term cyclic moisture aging on the strength and fatigue performance of a glass/vinyl ester pultruded composite system exposed to fresh and salt water found that the quasi-static tensile strength was seen to reduce by 24% at moisture concentration of 1% by weight. This reduction in strength was not recoverable even when the material was dried, suggesting that the exposure to moisture caused permanent damage in the material system. Even though the fatigue damage process of the control, fresh-water- and salt-water-saturated material was similar, the cyclic moisture absorption–desorption experiments altered the fatigue performance of the composite system tested. The elastic properties and fatigue strength results are shown in Fig. 2.28 and Fig. 2.29, respectively.

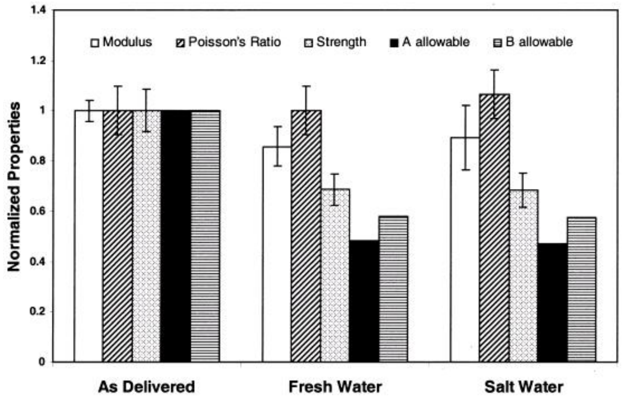


Fig. 2.28: Properties of control, fresh-water-aged and salt-water-aged materials [47]

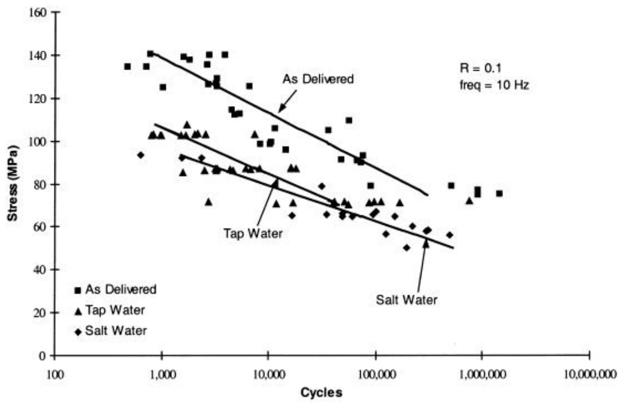


Fig. 2.29: S–N curves of the control, water-aged and 3.5% salt-solution-aged materials [47]

Experimental study conducted by Gautier *et al.* [48] has shown that glass fibre reinforced polyester pultruded composites immersed in water at different temperatures ranging from 30 to 100°C revealed three types of damage, i.e. osmotic cracking in the matrix, at the interphase and interfacial debonding. The result showed that the matrix osmotic cracking was the factor for specimen weight loss. The result also showed that the decreased of interlaminar shear strength (ILSS) was caused mainly by interfacial debonding, induced by differential swelling, and by osmotic cracking at the interphase but the matrix also contributed to the decrease. They finally concluded that the composite life time was greatly dependent on the ability of the matrix to micro crack under the service conditions.

2.7 Adhesive Bonding Technology

Adhesives have been successfully used for a number of decades in joining most of mechanical engineering components. Nowadays, the adhesives have been successfully used in textile, medicine and construction industry. The adhesive bonded joint offers or forms a major proportion of modern aircraft and automotive construction to reduce weight, mechanical stresses and production time. Adhesives have significant advantages over other mechanical joints such as rivets, bolts and screws of which adhesive bonding technology has a great potential to overcome excessive stresses concentration by spreading stresses over a larger area. This finally is able to permit thinner joining surfaces that are very important in low-weight structural applications.

2.7.1 Adhesive Selection

It has been found that epoxy adhesives exhibit better performances when used with concrete for FRP or steel plate strengthening application. It is also known that this epoxy system will absorb moisture (water). This water absorption was the factor that affects long-term performance and durability, especially with regard to long-term creep and development of interface corrosion [49]. The selection of suitable adhesive depends on several important factors as mentioned by Budinski [50]. Among the factors that need to be considered are as follows;

i. Service temperature
ii. Chemical level
iii. Duration of application
iv. Adherend materials

There are a few groups of adhesives system that can be considered for bonding most structural parts, and they are as follows:

i. **Epoxy:** Two-part adhesive system that is cured at room temperature based on epoxy-polyamide which has a shear strength as high as 13.8 MPa at 38°C and 0.68 MPa at 149°C. For better water uptake resistance, epoxy adhesive with polyamines hardener shows better performance compared to polyamide based hardener [50].

ii. **Anaerobic adhesives:** Polyester-acrylic resins which are cured with the absence of air. Suitable for metal to metal joints. Shear strength in excess of 13.8 MPa can be obtained on metal bond strength test.

iii. **Cyanoacrylates:** Suitable for metal bonding process which is cured by moisture absorption from adherends. Shear strength can be developed as high as 20.6 MPa.

2.7.2 Adhesive Mechanical Properties

In structural bonding applications, there are important mechanical properties that must be given full attention and understood in the design process, and they are as follows;

i. shear modulus
ii. shear strength
iii. maximum shear strain
iv. tensile modulus
v. tensile (peel) strength

All the important related properties should be obtained from the manufacturer or by established testing methods. This is important due to the effects from durability factors such as moisture ingression, temperature fluctuation etc. Referring to creep property, adhesives will creep under constant load even at the room temperature, especially at elevated temperature. Usually, thermosetting based adhesives have better creep resistance than thermoplastic adhesives. Fig. 2.30 shows two different behaviours of adhesives system that have the characteristics of ductile and brittle respectively. Brittle type adhesive normally fails at high stress level with low strain value compared to ductile adhesive system which shows high strain to failure.

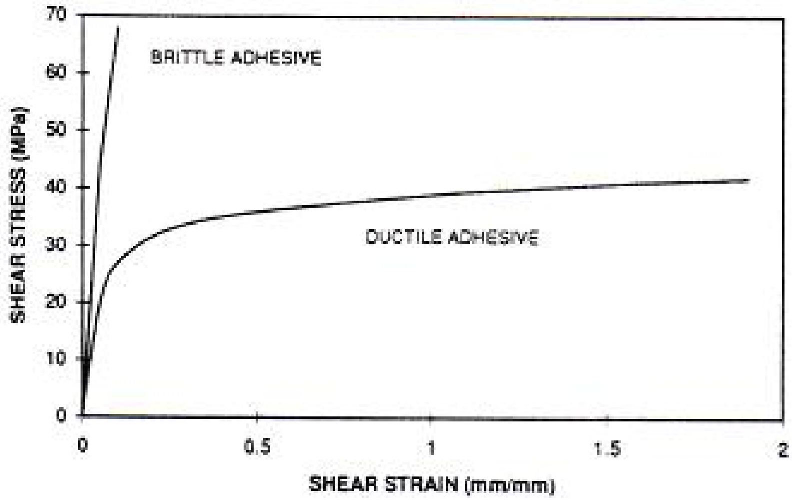


Fig. 2.30: Typical brittle and ductile adhesive behaviour [49]

2.7.3 Effects of Loading Configuration on Adhesive Joint

The joint structure typically loaded by several loading systems is shown in Fig. 2.31. The tensile, cleavage and peel loads, for example should be avoided because they will weaken the joint strength. In principal, the adhesive layers of the joint should primarily be stressed in shear or compression, the excessive strains (due to deformation) should also be considered at the area where non-linear behaviour of adherends or adhesive is expected [8,10,19,20,49].

In bonded joint, there are four main loading modes that may be subjected to most bonded structures;

i. Out-of-plane loads acting on thick adherends produce peel stresses.
ii. Tensile, torsion or pure shear loads imposed on adherends produce shear stresses.
iii. Out-of-plane tensile loads produce tensile and bending stresses.
iv. Out-of-plane tensile loads acting on stiff and thick adherends at the end of the joint produce cleavage.

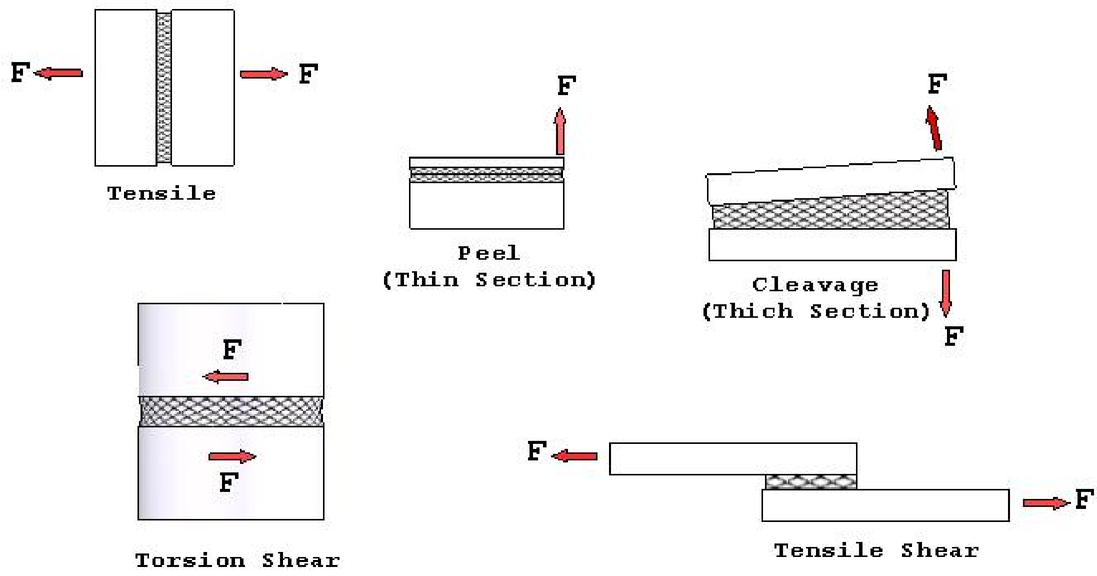


Fig. 2.31: Loading modes or type of stresses [49]

2.7.4 Advantages and Limitations of Adhesive Bonding

Adhesive may be the logical choice as a fastening method for bonding any structural materials for a variety of reasons [51]. However, there are advantages and limitations when using adhesive bonding. They are listed as follows;

(a) Advantages:

i. The ability to joint similar and dissimilar materials.

ii. The ability to minimize stress concentration usually associated with mechanical joints such as bolts, rivets and spot welds.

iii. Adhesive is not an electrical conductor, therefore, no formation of electrolytic corrosion in joining dissimilar materials.

iv. Ductile adhesive system is able to absorb shock and vibration which can increase fatigue life. Normally adhesive-bonded metal have ten times more fatigue life than mechanical joints.

v. Dissimilar materials thickness can be joined; for example, concrete beam can be joined to very thin FRP plate in strengthening application.

vi. Adhesive acting as a sealant in addition to bonding.

vii. The elimination of fastener holes allows lighter materials to be used and able to maintain equal or better mechanical properties.

(b) Limitations

i. Adhesives are more subject to deterioration due to environmental influences especially in adhesive-metal joints.
ii. Difficult to inspect the bond quality once assembled.
iii. Poor resistance to peeling type loading and may require additional fastener to support extra stresses (bonded-bolted joints).
iv. Polymeric based adhesives properties tend to degrade over time especially when expose to aggressive environment conditions.
v. Proper jigs and fixtures are needed for bonding process in order to apply heat and pressure which depend on bonding cycle.
vi. Most adhesives have limited shelf life.
vii. Less reliable when expose to extreme temperature above 300°C.

2.7.5 The Principles of Adhesive Bonding Technology for Structural Applications

The basic principles of adhesive bonded joints should be followed for the production of strong and durable adhesive bonds as well as to minimize the bond defects. There are several types of adhesive joint configurations and each type offers different criteria to be considered in design the connection. Davis and Bond [19] have listed a few important joint principles related to the application of adhesive bonding in practice. Among the important preferred principles are listed as follows;

i. The basic principle for the design of adhesive bonds is to design the joint such that the adhesive is always stronger than the unnotched strength of the adherends.
ii. The basic principle for adhesive fatigue design is, therefore, to ensure that the overlap length is sufficient to enable the adhesive shear stress to decay to near zero to make the joint resistant to creep and load effects.

iii. The basic principle of surface preparation is that the surface must be free of contamination, sufficiently chemically active to enable formation of chemical bonds between the adhesive and the adherends, and resistant to environmental deterioration in service, especially by hydration.

iv. The basic principle for the integrity of an adhesive bond is that the inspection will not assure quality, it must be obtained by the management of all aspects of the bonding process during production.

2.7.6 Factors Considered in Adhesive Joint Design

The strength of a joint depends on the yield strength (or ultimate strength for brittle materials) of the adherend, its modulus and thickness. The thickness of the adhesive bond is important and must be as thin as possible to avoid joint starvation. Special attention needs to be given to a few factors to make an appropriate and effective adhesive bond joint. Among the important factors that need to be seriously considered are as follows;

i. **Type of adhesive:** Different adhesive provides different bond strength and characteristic. The selection of the adhesive should be done carefully based on the type of joint, strength needed, materials to be connected and working environments.

ii. **Adherend materials:** The adherends used should be suitable to the adhesive. Each adherend has its own mechanical and physical properties that will provide different strength and durability.

iii. **Adherend preparations:** Adherend should be prepared by following the correct procedure to provide a good adhesion and absorption by the contact between adherend and the adhesive.

iv. **Curing process; temperature and pressure:** The adhesive will only provide high bond strength if it is completely cured. To reach this level, the bonding needs enough time, dry and clean environment and standard curing temperature. Incomplete curing process can cause bond slippage.

v. **Adhesive thickness:** The thickness of the adhesive should be controlled; not too thick or too thin. Thick bond layer will create an unexpected force and moment, and will finally produce peel failure. Thin bond thickness could cause lower bond strength.

2.7.7 Bond Mechanism

The theory considers adhesion to be the result of the mechanical interlocking of polymer adhesive into the pores and other superficial asperities of adherend. The roughness and porosity of adherend are generally the factors of wetting ability if the adhesive is sufficient, as shown in Fig. 2.32. Otherwise, the non-wetted parts originate failures. However, mechanical interlocking is not a mechanism at the molecular level. It is merely a technical means to increase the absorption of the adhesive to the adherends at macro level [52].

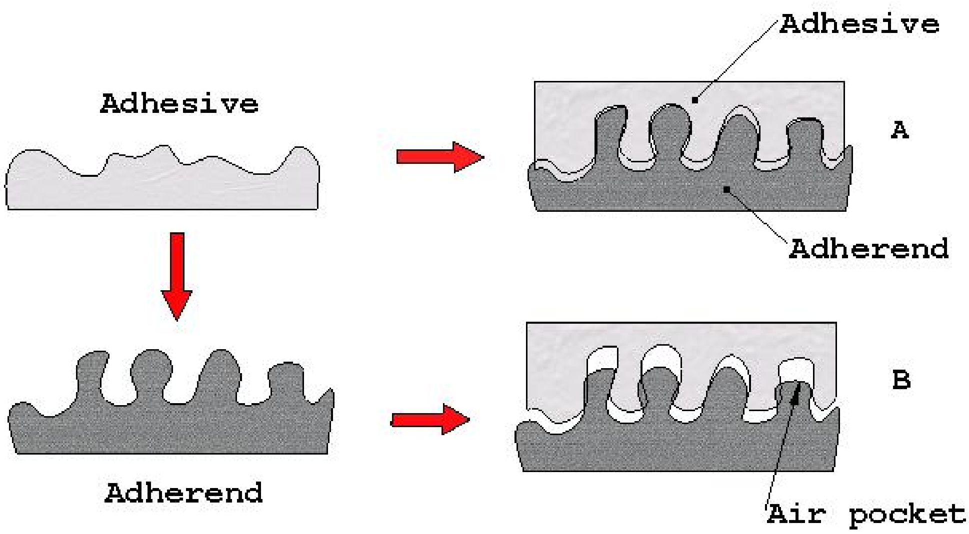


Fig. 2.32: Good wetting (A) Poor wetting (B) [52]

2.7.8 Adhesive Joint Design

By referring to Eurocomp Design Code and Handbook [49], bonded joint can be defined as where the similar or dissimilar substrates (adherends) bond surfaces are held together (i.e. by mechanical or chemical mechanism) by means of structural adhesive system.

Another important parameter related to adhesive joint design is the bond transfer length which is defined as the distance from loaded (stressed) end of the joint to the point where the exponential strain profiles reach zero strain [53]. In addition to that, Nakaba *et al.* [54], have defined the effective bond length as the distance between two points that correspond to 10% of the maximum bond stress which significantly can be related to the adherend stiffness (i.e. adherend tensile modulus, E *x* adherend thickness, t). They have also reported that the effective bond length for most studies related to FRP-adhesive-concrete conducted by previous researchers [10,21,23,53,55] had confined within 100 mm bond region.

Referring to Eurocomp Design Code and Handbook [49], the joint design process should start by recognizing the joint requirements such as for supporting and distributing the internal forces and moments. The following stage is selecting the joint category normally determined by loading configuration or by the required joint efficiency as a fraction of the strength. The geometry of the adherends, suitability of the fabrication, component dimensions, manufacturing environment and number of components to be produced must also be considered. Other factors include service environment and the lifetime of the structure, requirements set for the reliability of the joint, disassembly or not, aesthetics and cost. In designing adhesive joint the basic characteristics of adhesives must dictate the design. The type of joint techniques used in adhesive bonding is shown in Fig. 2.33.

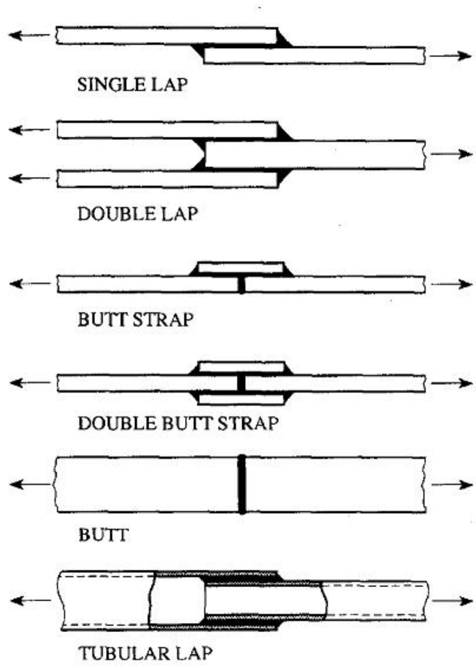


Fig. 2.33: Types of adhesive joint techniques [56]

2.7.9 Adhesive Bond Strength

The joint strength is also affected by the joint geometry of certain configuration. The most basic problems of bonded joint are the unavoidable shear stress concentrations and inherent eccentricity of the forces. From Fig. 2.34, it can be seen that the shear stresses are at the maximum at the end of the overlap. The effects of eccentricity are the greatest in lap and strap joints. It should be known that the static load-bearing capacity of a bonded lap or strap joint cannot be increased significantly by increasing the lap length beyond the minimum needs. But, the bond length must be long enough to provide a moderate loaded adhesive area in the middle to resist creep deformations of the adhesive.

Fig. 2.34 shows the typical locations of possible failure initiation and critical strength. It can be seen that when the joint (i.e. single lap) is loaded with in-plane loads, the concentration of stress failure exists at the ends of the over lap. Fig. 2.35 shows the shear stress distribution along the bonded length and the location where higher shear stresses occurred. The higher shear stresses location can be said to be the region of failure initiation.

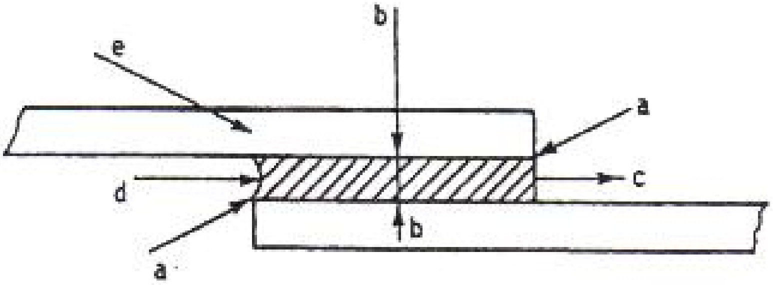


Fig. 2.34: Areas of failure initiation and critical strength [49]

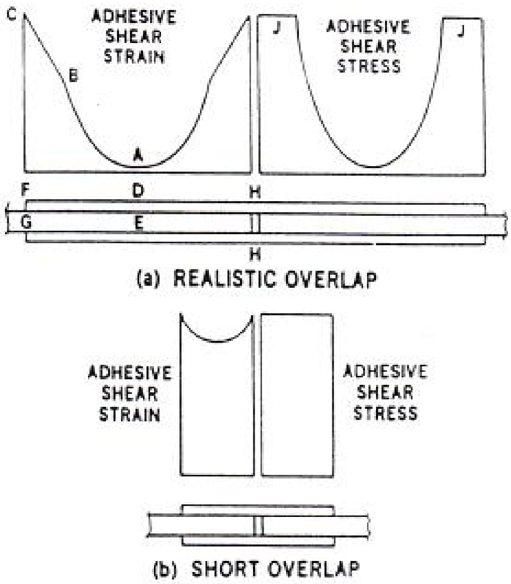


Fig. 2.35: A typical adhesive shear stress distribution in a lap joint according to elastic-plastic model [49]

Referring to the study conducted by Horiguchi and Saedki [23] on bond strength of FRP-concrete bonded system, they found that bond strength, f_{bok} and concrete compressive strength, f'_{ck} was highly correlated. The respected equation that governed the relationship was given as follows;

$$f_{bok} = (0.28)\, f'_{ck}{}^{(2/3)} \qquad [2.1]$$

In addition to the study of FRP bonded system to concrete member, Brosens and Van Gemert [57] had produced a design rule (i.e. equation) that was able to predict the bond fracture load, P_{max} (i.e. load at cracking level) in initial bond force transfer region. Their rule was able to overcome the difficulties in defining "fracture energy" in the equation developed using non-linear fracture energy concept (i.e. by Taljsten [58]). Their bond fracture load equation that referred to single lap joint was defined as follows;

$$P_{max} = (w \times L_B \times f_{ctk,s})/2 \qquad [2.2]$$

2.7.10 Bond Elastic Properties and Deformation

By assuming that the deformation of a double-lap joint follows the deformation shown in Fig. 2.36 (single-lap joint), theoretically the deformation and initiation of bond failure occur at the loaded end (i.e. the most stressed region). The upper and lower parts represent adherends, while adhesive the middle. The members deform concentrically and the adhesive in shear when the load is applied. The specimen can be categorized into two types; as rigid members and as elastic members. If the members were rigid, equal amount of load would be transferred along the adhesive, and the shear deformation would be equal in all parts of adhesive. In reality, members always have elasticity and will deform continuously throughout their lengths. The greater the amount of load transferred at the centre of the overlap, the higher the displacement between the members there.

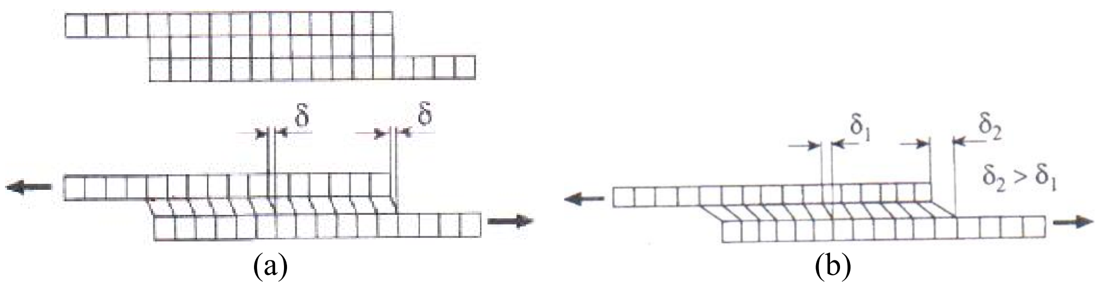


Fig. 2.36: (a) Deformation of rigid members (b) Deformation of elastic members [49]

2.7.11 Bond Formulation under Tension-Compression Loads

The double lap joint (Fig. 2.37) is a balanced construction configuration joint that consists of two outer adherends that are bonded on both sides of centre (inner) adherend. In a well symmetrical double lap joint, the centre of the adherend experiences no net bending moment, but the outer adherend will (if it is thick), which could increase tensile and compressive stresses at loaded ends.

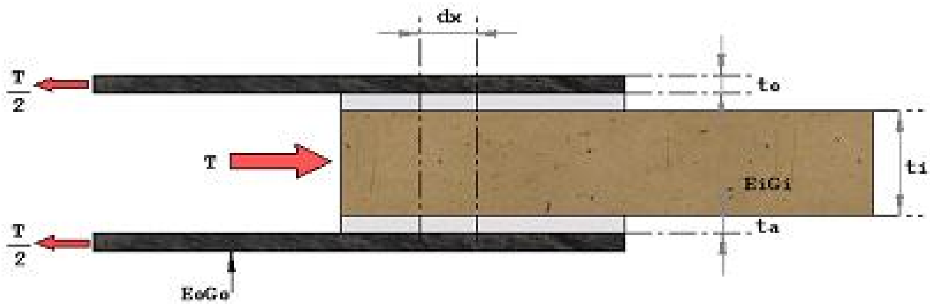


Fig. 2.37: Double lap joint configuration specimen under tension-compression (pull-out) loads [10,21,53,55]

The joint is designed based on a standard bond area (i.e. bond length *x* bond width), maximum proportion of bond area that contributes to strength, the direction of maximum stress applied to high strength area and the minimum stress in the direction of the weakest joint. When the adherends are subjected to the tension load, the loading effect can be divided into normal force, shear force and internal bending moment. It is reasonable to ignore axial stress in the adhesive layer as it is regarded as thin layer and is assumed to be less stiff than the adherends. Another assumption is that the strain in the vertical direction of the adhesive is zero, making the shear stress and shear strain to be assumed constant over the adhesive layers.

The development of a mathematical model for FRP plate-adhesive-concrete bonded system under tension-compression (pull-out) loading configuration can be referred to the elementary force diagram shown in Fig. 2.38. In the model, the FRP plate, adhesive layer and concrete prism cross-section are assumed to be constant along the bond length. A simple elastic model for this joint can be thus established by treating the plate and the concrete prism as being subjected to axial deformations, while the adhesive layer is assumed to be subjected to shear deformations only, i.e. both adherends are assumed to be subjected to uniformly distributed stresses, with any bending effect neglected, while the adhesive layer is assumed to be subjected to shear stresses which are also constant across the adhesive layer thickness. It should be noted that in such a model, the adhesive layer represents not only the deformation of the actual adhesive layer but also that of materials adjacent to the adhesive layer and is thus also referred to as the joint interfaces. Therefore, from Fig. 2.38, the adhesive shear (bond) stress, τ_a governing equation is given by equation [2.3]. The equation is developed by neglecting the adherends' shear deformation and also assuming linear shear stress distributions through the thickness of the adherends.

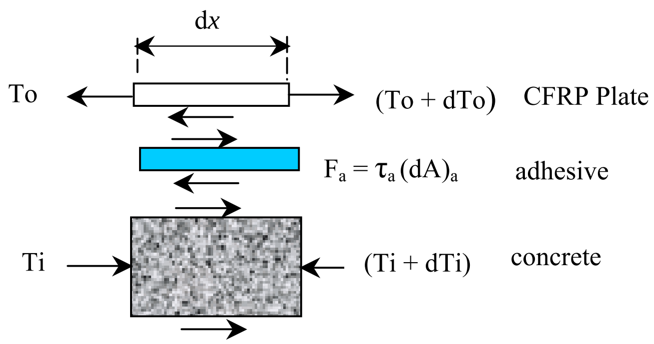


Fig. 2.38: Force analysis on elementary bar model [59,60]

$$\tau_a = \frac{1}{\left[1 - e^{-2\beta L}\right]}\left[\frac{T}{2L}\right]\left[e^{-\beta x} - e^{\beta x} \cdot e^{-2\beta L}\right] \qquad [2.3]$$

where, $\beta^2 = \alpha^2 \lambda^2$

$$\lambda^2 = \frac{G_a}{t_a}\left(-\frac{2}{E_i t_i} + \frac{1}{E_o t_o}\right) \text{ and } \alpha^2 = \left[1 + \frac{G_a}{t_a}\left(\frac{t_i}{6G_i} + \frac{t_o}{3G_o}\right)\right]^{-1}$$

2.7.12 Adhesive Bond Surface Treatments

Adherend surface treatment is really an important parameter that will affect an adequate joint strength if not properly prepared. Therefore, all the bond surfaces shall be properly treated prior to bonding. In order to produce a good bonding performance, the entire adherends' bond surface shall be treated by the following procedure:

i. Solvent degreasing using a clean absorbent material which does not itself contaminate the surface.
ii. Abrading using medium grit abrasive paper (i.e. for FRP composite), sandblasting (i.e. for metal or concrete), etc.
iii. Degreasing.

During the surface roughening process, the pressure applied (i.e. by any type of tool) shall be adjusted to suit the condition as not to damage the adherend material structure (i.e. not to produce permanent stresses within material structure). Commonly, the prepared surface must be pretreated immediately after surface treatment to avoid contamination or voids that can cause poor bonding.

2.7.13 Adhesive Bond Design Principles

In general, the loads imposed on the bonded joint structure must be obtained from the whole structure analysis. The bond line must be capable of transferring the applied loads between the joints members, while the adherends are capable of with-standing the joint induced internal loadings. The evaluation of the components basic strength is a part of the component in the design process.

The experimental specimen to be tested is designed based on analytical models for plate-to-plate connection and supplemented by testing. The assumption made is that the joint is a perfect bonding between the adhesive and the adherends. This means, there is no slip occurring along the bond area and the force applied is transferred uniformly to each part of the adherends. It shows that the failure of cohesive in the adhesive or adherend always occurs before the adhesive failure at the interface. The assumption may become invalid if the following matter occurred:

i. Unsuitable chemical of the adhesive and adherends. The adhesive cannot provide a good bonding and high strength needed. Besides, the adhesive will give a chemical reaction between the adhesive matrix and the adherends matrix.
ii. Inadequate surface treatment. For examples, the surface is not roughened perfectly, the surface of bonding area is contaminated and not fully degreased by the solvent, the pressure applied while bonding is also not enough.
iii. Environment factors such as temperature and pressure during bonding. The bonding process should not been done during high humidity where the water will dissolved between the adhesive pores and will affect the bond strength. There must be enough time for the adhesive to cure and should be done in suitable dry environment.
iv. Other bonding defects.

Referring to Fig. 2.39, it can be seen that the different type of joint has its own mode of failure. For double lap joint (i.e. same characteristic as double strap joint), the major problem is peel failure if compared to the other joint techniques which are likely to have shear failure.

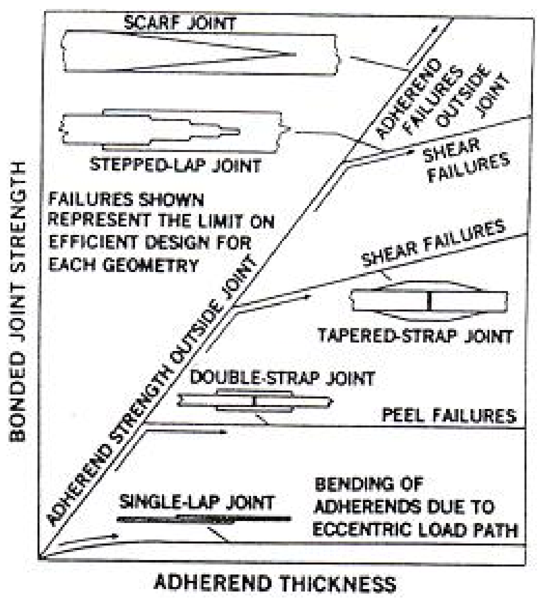


Fig. 2.39: Relative joint strength of various joint configurations [49]

2.8 Shear Test Rigs for Materials Research

Over the years, there has been a considerable interest in the development of suitable shear test rigs. Although the torsion test on thin-walled tubes is generally regarded as providing a uniform and pure state of shear, grip-related failure can arise, and specimen preparation is more tedious than other alternative method.

The Arcan test method was first introduced in 1973 by Arcan [61]. The test method was developed to overcome such an existence of other stress components (i.e. tensile stress) besides the shear stress in the final measurement. To produce a uniform state of plane-stress for a solid specimen, Arcan *et al.* [62] first developed this test method to evaluate the longitudinal and through-thickness shear modulus of a unidirectional laminated CFRP composite, i.e. the mechanical properties of isotropic as well as orthotropic composite materials under uniform plane stress condition, by means of a specially designed butterfly-shaped specimen. The advantage of Arcan test method compared to cylinder-torsion test method was the test fixture could provide a state of uniform pure shear stress in an area known as a significant section by a plane stress loading. Apart from that, this test method has also proven that anisotropic composite specimen could be tested with a high degree of accuracy and reliability.

2.8.1 The Evolution of the Arcan Test Fixture

Arcan *et al.* [62] proposed a biaxial test fixture, commonly known as the Arcan test fixture, to produce biaxial states of stress. The compact nature of the Arcan fixture enabled the obtaining of shear properties in any in-plane directions in a relative manner. The results were in agreement with those obtained from cylinder-torsion tests. The early design concept of the Arcan fixture is shown in Fig. 2.40.

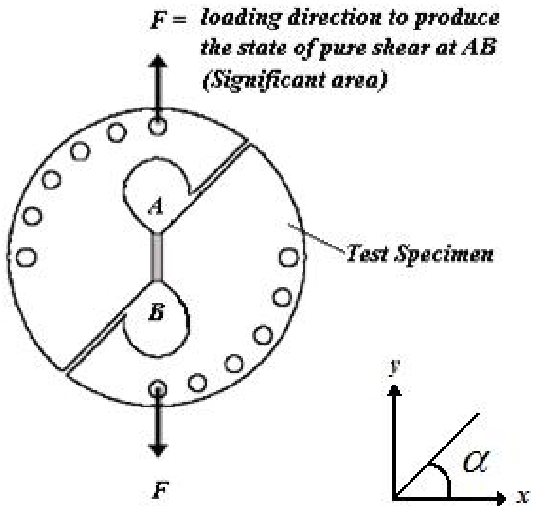


Fig. 2.40: The early concept of Arcan test method [62]

In their early design concept, the test fixture-specimen was prepared and fabricated from the material to be tested. In the configuration, the testing is performed in shear mode. The hatched area denotes the deformation zone. By applying tensile force, F, in different directions, combinations of tension and shear loading are possible to be produced. This method includes pure shear as a special case, when the angle $\alpha = 90^{\circ}$. The principle behind the geometry of the specimen is that in the pure shear zone, the isostatics will intersect the sheared cross-section (AB in Fig. 2.41) at an angle of $\alpha = \pm 45^{\circ}$.

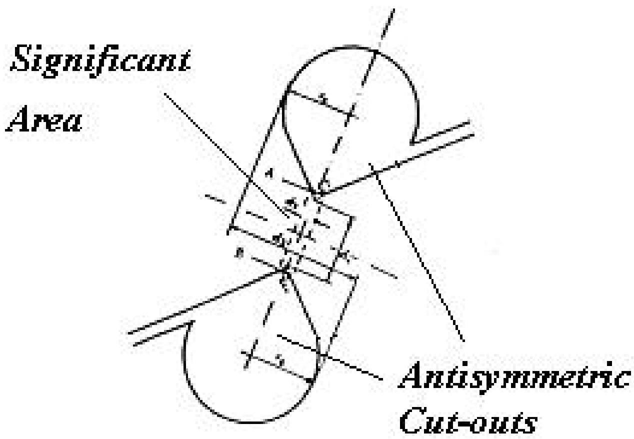


Fig. 2.41: Significant section of the Arcan's butterfly specimen [61]

In 1978, Arcan *et al.* [62] have modified the previous test fixture by bonding the test specimen on the aluminium circular plane with anti symmetric cut-outs as shown in Fig. 2.42.

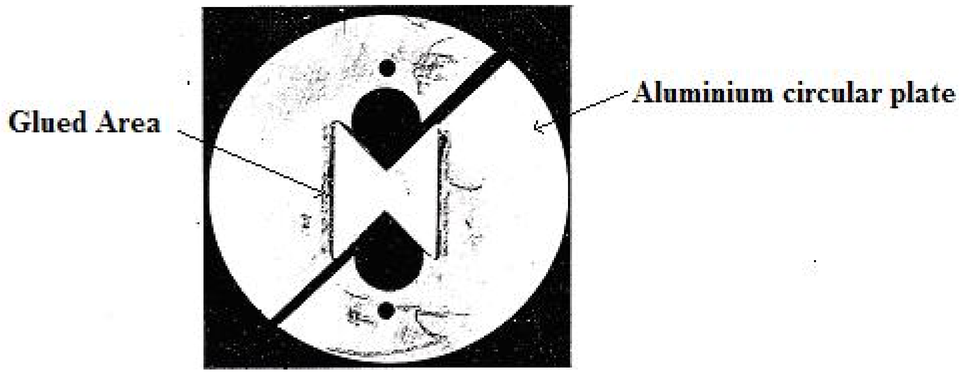


Fig. 2.42: Butterfly specimen bonded to aluminium circular plate test fixture [62]

The development of Arcan test fixture was continued by Yen *et al.* [63]. The modified Arcan fixture was made of two pairs of stainless steel parts, each pair equivalent to one half of the original Arcan fixture. A butterfly shape cut-out was machined to half the thickness in each part to house the specimen. Three holes were drilled at each part to allow for the tightening of the two parts together with screws. The butterfly specimen which was joined on either side of two half circular grips as in Fig. 2.43 were connected to a universal testing machine at the top and bottom, respectively. The grips together with the butterfly specimen formed a circular disk with two anti-symmetric cut-outs.

Fig. 2.43: Modified test fixture and butterfly specimen set-up by Yen *et al.* [63]

The modified Arcan fixture and its butterfly specimen were designed to determine the shear moduli, non linear-stress strain response, and strength of thick section pultruded composites under shear, combined with different biaxial stress conditions. The modification proposed by Yen *et al.* [63] included bolting a butterfly shaped specimen between two identical halves of the Arcan fixture. Fig. 2.44 shows a schematic of the modified Arcan fixture with the butterfly specimen.

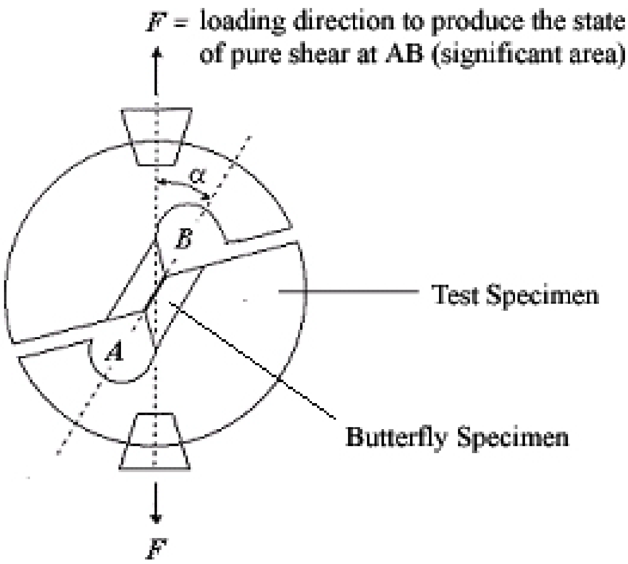


Fig. 2.44: Arcan fixture and butterfly specimen loading configuration [63]

The fixture was flexible to accommodate the pultruded specimens with various thicknesses. The butterfly specimen design is shown in Fig 2.45. Six units of 6.4 mm diameter sleeve bolts were used to transfer the load from the fixture to each side of the specimen and the bolts were hand-tightened. The significant section of the specimen AB was designed in such way that the state of stress on AB was as uniform as possible.

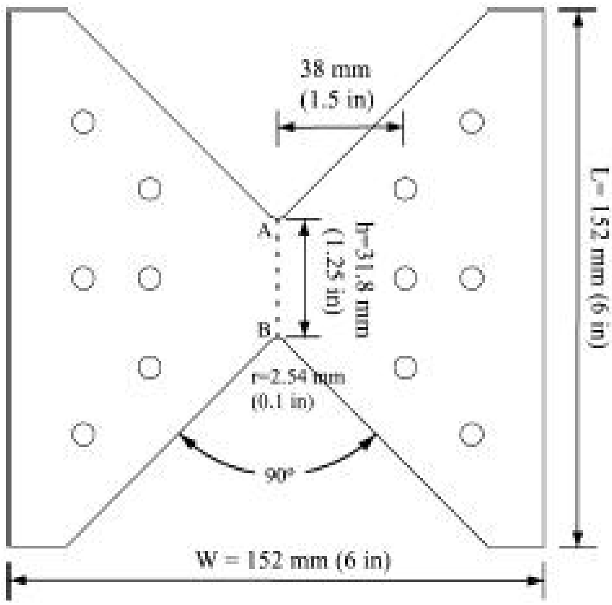


Fig. 2.45: Butterfly specimen geometry used by Yen *et al.* [63]

The objective of their study was to modify the Arcan test fixture in order to improve shear test data. From the strain and loading test data, the relationship between the applied shear stress and the strain in $\pm 45°$ directions was established. The shear stress-strain data for the Graphite/PEEK composite specimen is shown in Fig. 2.46.

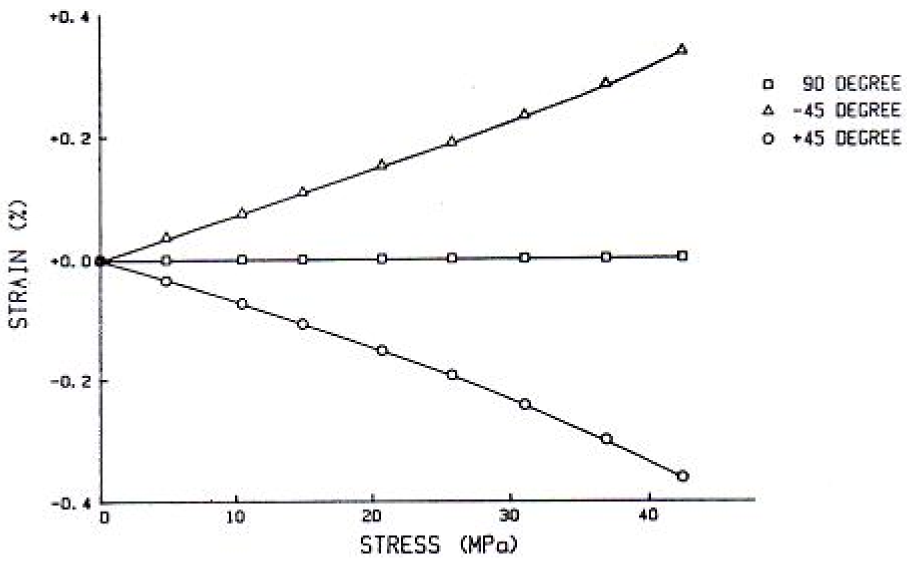


Fig. 2.46: The strain results of a Graphite/PEEK specimen in shear [63]

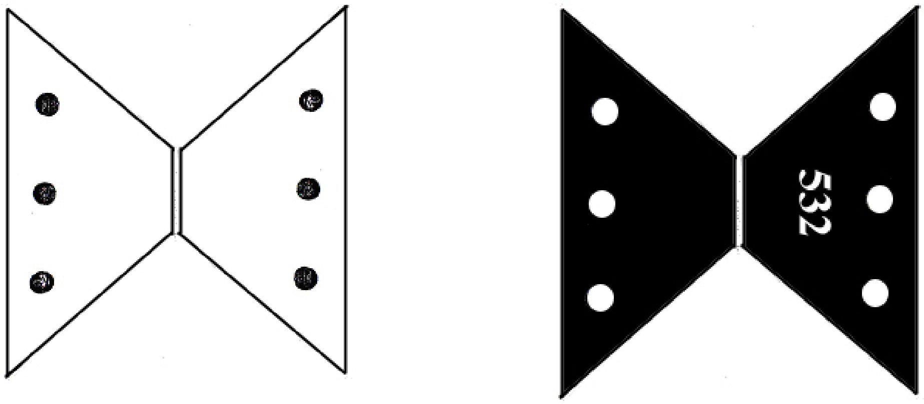
The strain profile of Graphite/PEEK specimen in shear has verified that state of pure shear was present during the experiment. This was deduced from the fact that the straining transverse to the applied load was practically zero, thus indicating no normal stress in that direction. The principal strains in both directions of -45° and +45° were then used to determine the shear strain. This was done by subtracting the strain in the -45° direction from that of +45° direction. As a result, a shear stress and shear strain relationship for each gauge specimen was obtained. The calculated shear moduli of aluminium, Plexiglass and Graphite/PEEK test results are given in Table 2.6.

Table 2.6: Average shear modulus and shear strength test results of various materials [63]

Material	Shear Modulus, G (GPa)	Shear Strength, τ (MPa)
Aluminum	28	220
Plexiglass	-na-	36
Composite (Graphite/PEEK)	6.0	83

For the thermoplastic composite material, the elastic shear modulus and shear strength obtained from the tensile test were used for comparison purposes. It was found that the shear properties obtained from the Arcan shear test method were in agreement with the reference data provided by Arcan *et al.* [62].

The fracture surfaces for the aluminium and thermoplastic composite were found parallel to the direction of the applied load, as shown in Fig. 2.47 (a) and (b). This appearance indicated failure mechanism due to a state of shear stress. It should be pointed out that the fracture of graphite/PEEK specimen occurred at a location slightly away from the gauge section. This could be due to the misalignment between the loading axis and gauge section or the initiation of sharp edges or formation of crack within the region.



(a) (b)

Fig. 2.47 (a): Shear failure of an aluminium specimen and **(b):** Shear failure of a Graphite/PEEK specimen [63]

The fracture mechanism of the Plexiglass initiated from the notch roots of the specimen. As a result, the fracture surface was generated and found 45º from the loading axis, which was the direction of the tensile principal stress corresponding to the state of pure shear, as shown in Fig. 2.48. This fracture mechanism supported the fact that brittle materials generally fail in a tensile mode, which was also found in the Iosipescu shear test of vinyl ester conducted by Sullivan *et al*. [64].

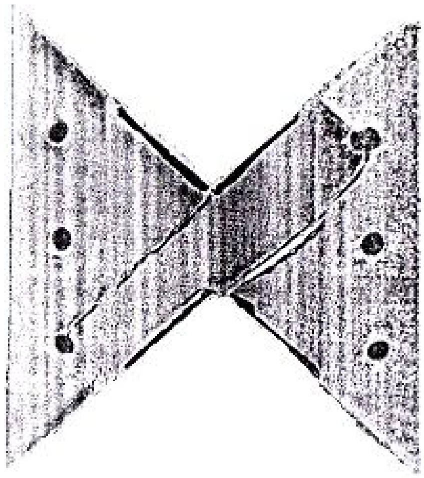


Fig. 2.48: Brittle failure of Plexiglass specimen [63]

From the experiment conducted by Rani El-Hajjar and Rami Haj-Ali [65], the Arcan fixture with butterfly specimen were used to determine the in-plane shear properties of thick-section pultruded FRP composites. The main objectives of their experiment were to analyse the effect of notch radius on the shear properties study, the strain profiles along the AB section, and to determine the material's shear modulus. There were three notch radii selected to determine the most appropriate radius of 1.27 mm, 2.54 mm and 5.05 mm. Fig. 2.49 shows the effect of the notch radius on the shear stress profile along the gauge section for FRP axial orientation. A normalised stress profile near to 1.0 was found near the centre for the specimen with a notch radius of 2.54 mm.

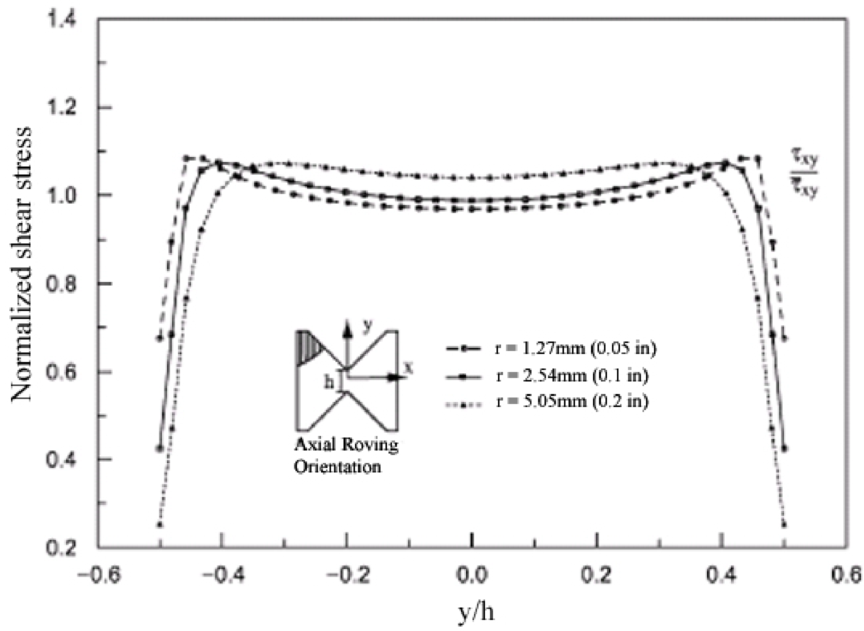


Fig. 2.49: Effect of notch radius on shear stress profile along gauge section [65]

On the other hand, the simulation by isotropic assumption and orthotropic value showed that the blunted notch resulted in a lower stress concentration near the notch tip, with a more gradual stress built up compared to the sharp notch as shown in Fig. 2.50. The stress profile was uniform near the blunted notch tip resulting in a normalised shear stress closer to 1.0.

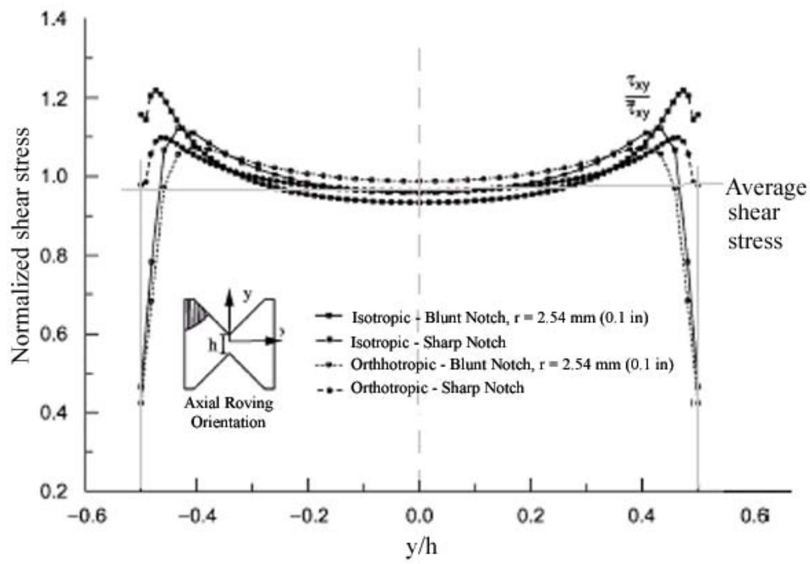


Fig. 2.50: Effect of sharp notch on shear stress along the gauge section [65]

From their test data, a stress-strain curve was plotted and it can be noted that all specimens perfectly failed in brittle manner. The shear stress versus shear strain curves shown in Fig. 2.51 verified that a state of pure shear was present during the testing because the curves are linearly propagated. This is also deduced from the fact that the straining transverse to the applied load was practically zero, thus indicating no normal stress in that direction [63].

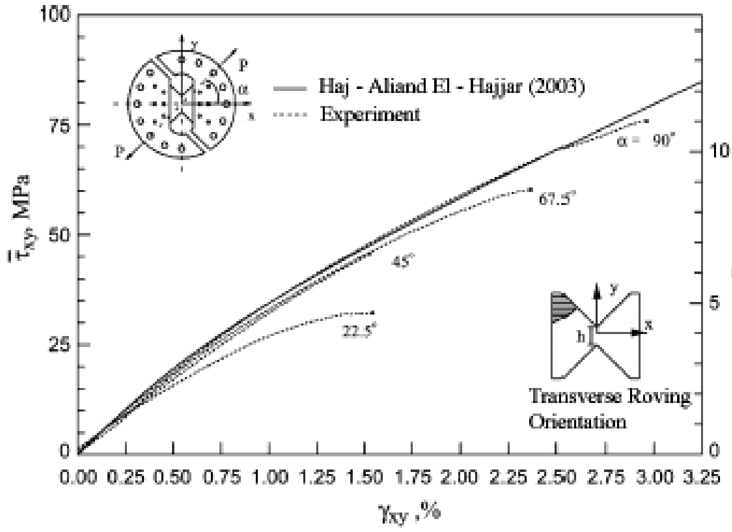


Fig. 2.51: Shear stress-strain response from Arcan shear test [65]

Both strains, ε_{-45} and ε_{45} are linearly propagated and almost symmetry along *x*-axis as shown in Fig. 2.52. This indicates that the testing method was reliable as the strain data obtained were balanced in each direction, and could be used to determine the shear properties, shear modulus, and shear strain of brittle materials, especially for Fibre Reinforced Polymer composites.

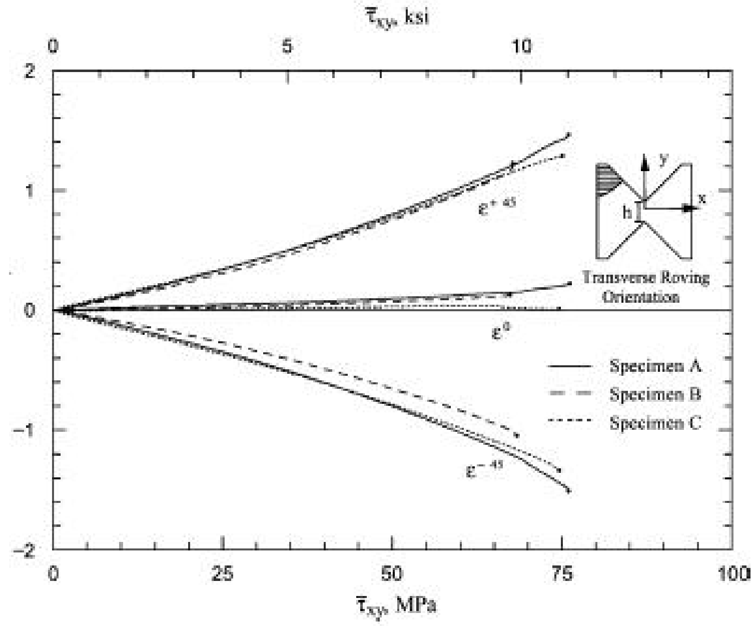


Fig. 2.52: Measured strain profiles at centre of transverse butterfly specimen during 'pure shear' test [65]

2.8.2 Load Sustainability Rig for Durability Experimentation Programme

The Fibre Reinforced Polymer composites are the choice in most industries to date due to their durability and reliability aspects in certain applications. In construction, the FRP composites, especially Carbon Fibre Reinforced Polymer (CFRP) or Glass Fibre Reinforced Polymer (GFRP) in the form of pultruded plates or laminated sheets, have been used for upgrading or repairing various types of reinforced concrete members around the world. Although many researches are being done to date, most of the works focus on short-term mechanical performances rather than long-term durability aspects. FRP plates externally bonded to the reinforced concrete members need to be investigated for their full composite action or joint efficiency of FRP plate-adhesive and concrete-adhesive interface. This is the region where most environmental components such as solar ultraviolet radiation and moisture play their role to reduce the structural bond integrity in long-term service.

Durability studies related to flexural performances of steel plate-concrete beam bonded system exposed to natural environmental condition under sustained load were conducted by various researchers around the worlds. In order to study the long-term performances of plate bonded system, the researchers have used designated full mechanical rigs in such a way that created a sustainable four point flexural loads imposed onto a pair of externally bonded steel plate-concrete system.

Among the researchers that actively conducted the study related to durability aspect of steel to reinforced concrete bonded system performances were Calder [66-70], Swamy *et al.* [71] and Ong and Mansur [72]. They used mechanical rigs as shown in Fig. 2.53 that imposed flexural loads onto a pair of externally bonded steel to reinforced concrete beams. Their rigs were proven to sustain the imposed load throughout the experimentation exposure period.

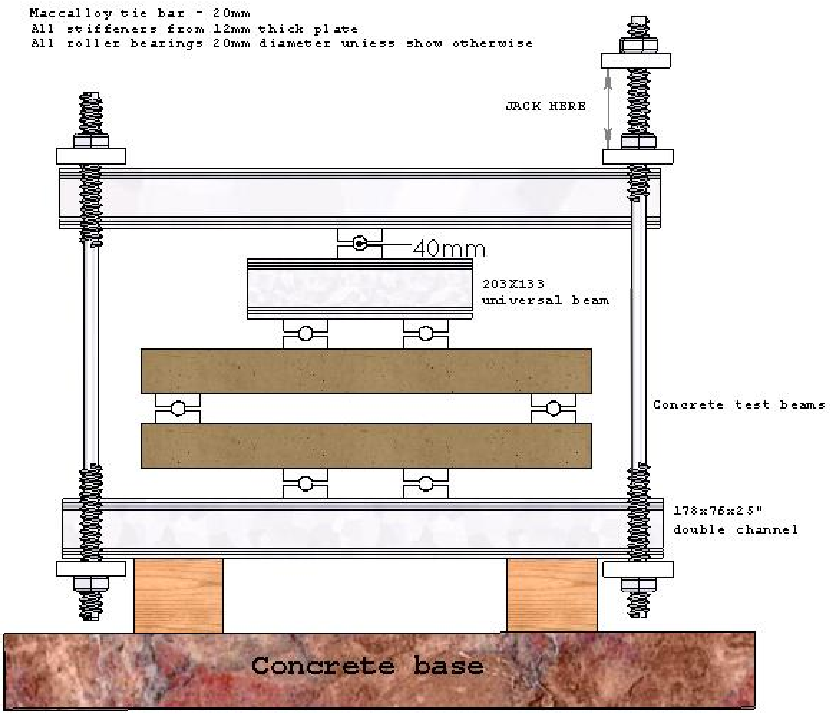


Fig. 2.53: Experimental rig design concept by Calder in year 1979 [66]

For short-term and long-term bond durability study, Swamy *et al.* [71] and Mukhopadhyaya *et al.* [10] used test rig and specimen configuration as shown in Fig. 2.54 (a) and (b). It can be seen that FRP plates and concrete were subjected to tension and compression respectively. The effect of relative loading configuration for both materials produced shearing effect on epoxy adhesive. By eliminating the effect of peeling stresses, another important design element was this kind of configuration representing the actual condition at FRP-concrete interface due to flexural load of RC members externally bonded by either steel or FRP plate system as shown in Fig. 2.54.

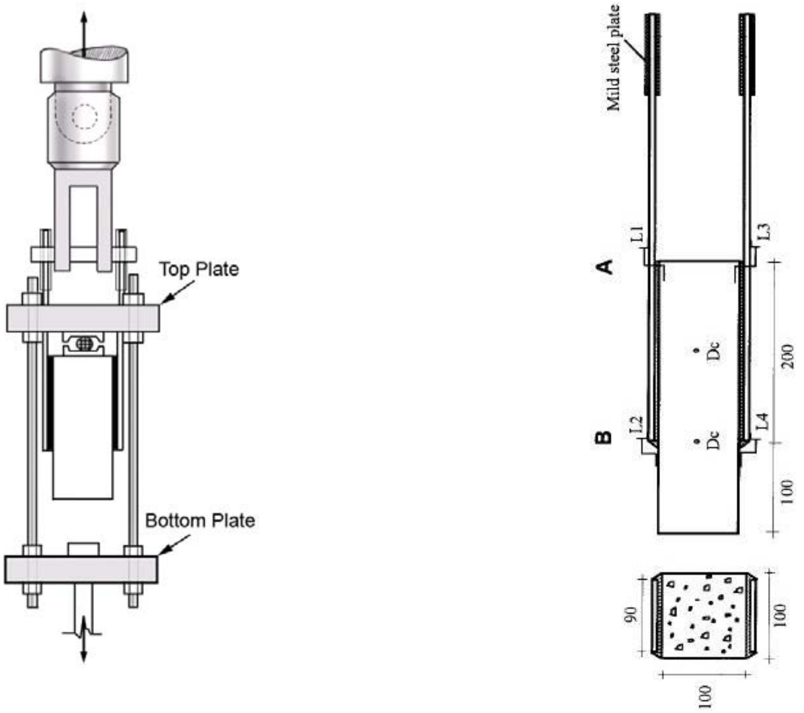


Fig. 2.54: Test rig and specimen geometry used by Mukhopadhyaya *et al.* [10]

2.9 Conclusions

i. Environmental stability factors are among the key elements that could affect the bond strength due to the mechanical and chemical properties changes in the bond interfaces.

ii. The changes in weather climatic condition, atmospheric acidification, loss of biodiversity and marine pollution are among the issues that contribute to global warming. From the literature, it shows that some parts of Peninsular Malaysia are affected by these phenomena.

iii. Adhesive joints are limited by various factors due to formation from polymeric based materials. Environmental factors such as solar ultra-violet ray and moisture are among the elements that can lead to the degradation of structure bond integration.

iv. The design, development and fabrication of test rigs for bond durability study are able to proof and produce reliable results that are useful for future researches, especially ones related to long-term structural bond performances under weathering effects.