Research Report

Of

EFFECTS OF ELEVATED TEMPERATURE CURING ON GLASS TRANSITION TEMPERATURE OF CFRP/CONCRETE BOND

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IN

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By

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EFFECTS OF ELEVATED TEMPERATURE CURING ON GLASS TRANSITION TEMPERATURE OF CFRP/CONCRETE BOND

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The Dissertation was submitted to the Department of Civil Engineering of the University of Moratuwa in partial fulfillment of the requirement for the Degree of Master of Science

Department of Civil Engineering
University of Moratuwa
August 2021

Declaration

I confirm that, except where indicated through the proper use of citations and references, this is my original work. I confirm that subject to final approval by the Board of Examiners of the University of Moratuwa, a copy of this Dissertation may be placed upon the shelves of the library of the University of Moratuwa and may be circulated as required.

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W. K.K. Rathnasiri Date

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To the best of my knowledge, the above particulars are correct.

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Prof. Gamage, J.C.P.H (Supervisor) Date

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Abstract

Strengthening of existing structures made out of concrete, all around the world is an increasing requirement due to many reasons like aging, insufficient maintenance, and the degradation due to environmental impact, as well as due to increases of the applied loads and due to requirement of complying with the modern standards. Carbon Fiber Reinforcement Polymer, CFRP, one of the budding and potential technologies in the structural strengthening process. As such lots of researchers who wish to continue their higher studies and knowledge gaining in structural engineering have involved researchers in structural strengthening using CFRP.

Laying CFRP fabrics and composites using epoxy adhesives, along the external surfaces of structural elements are the popular method for a strengthening of structural capacities. These externally laid CFRP fabrics are subjected to elevated temperatures due to environmental conditions. The exposure to such elevated temperature affects the strength of the CFRP/Concrete bonds, because of the low glass transition temperature (T_g) of these epoxy adhesives that have been used to create the bond between CFRP and concrete substrate.

A slight increment of T_g is also contributed to enhancing environmental resistance of strengthened outdoor members which directly expose to the environmental fluctuations. Curing of the CFRP/epoxy/concrete bond in an elevated temperature environment may enhance the bond performance while improving its T_g. However, it is important to ensure a safe temperature range in curing without affecting the performance of the concrete part of the system. This study focuses on determining the safe temperature range, which may be used as raised temperature curing of the CFRP/Concrete composites and determination of bond characteristics for the corresponding temperature applied for curing.

A total of twenty-five single strap joints were prepared under two different curing conditions. The impact of curing at moderately elevated temperature (75°C) on CFRP/Concrete bond strength was examined for both ambient and elevated temperature conditions.

The test results revealed that the raised temperature curing has a remarkable effect on the T_g of CFRP/Concrete bond. A considerable improvement of T_g was noted in the joint with elevated temperature curing when matched with the ambient temperature cured CFRP/Concrete specimens. The strength degradation of the bond for a certain temperature exposure is also reduced with increased T_g of the joint.

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Throughout the Research studies and writing of this dissertation, I have received a great deal of support and assistance.

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List of symbols, notations, abbreviations, and acronyms

CFRP – Carbon Fiber Reinforcement Polymer

T_g - Glass Transition Temperature

FRP – Fiber Reinforcement Polymer

FEM – Finite element modeling

US – United States

UV – Ultra Violet

01. Introduction

1.1 Research Background

Most civil engineering structures constructed using reinforced concrete technology, in the recent past have to be strengthened due to various reasons. This is not only due to weakening of reinforced concrete structures as a consequence of aging, insufficient maintenance, and dilapidation. Further, it may be due to the requirement of increasing the applied loads and the requirement of complying with the modern standards.

Carbon Fibre Reinforced Polymer (CFRP) technology is getting popular around the world for retrofitting concrete erections like bridges and buildings, to enhance the shear strength, flexural capacity, and torsional capacity of concrete. Several types of CFRP strengthening methods are applied in the structures, which are strengthened already, according to the method of delivery to the site and the method of installation. The wet lay-up technology can be identified as the most popular installation technique among them to apply CFRP fabrics on the concrete elements as external reinforcement for concrete structures [3].

Under the wet lay-up method, CFRP fabrics have to be saturated with the selected epoxy adhesive polymer resin, and placed on the concrete element going to be strengthened. The epoxy resin performs as an adhesive, and as the matrix with the CF fabric as well. The adhesive layer, between CFRP and concrete surface, therefore plays an important role, by forming a resin continuum in between the CFRP fabric and the concrete element [14], acting as transferring medium for shear stresses between strengthened concrete element and the CFRP fabric. Hence, adhesives can be identified as the one of the most important components of the CFRP/concrete system.

The epoxy adhesives, which applied externally for FRP applications are frequently subjected to the temperature variations in the environment. These epoxies are very sensitive to excessive heat. Exposure to excessive temperatures may cause the sudden strength loss of the FRP/concrete bond. Further, this may result in the delamination of the FRP fabric declining its effectiveness [12]. Past studies, carried out by few researchers to discover the impact due to the higher level of temperatures on the bond behavior of CFRP/concrete specimens [12, 8]. According to these findings, declining of the bond strength was identified with higher temperature levels, which are closer to the glass transition temperature (T_g) of the polymer adhesive or higher than that [12]. All the CFRP/concrete bond failure happens as an adhesive failure for the specimens, which are tested for elevated temperatures ranging 50 °C – 70 °C. At a lower temperature than 50 °C, a mixture of the concrete rupture failure and the adhesive failure was observed. Bond strengths of CFRP/concrete samples, which were subjected to four different temperatures, 20 °C, 30 °C, 40 °C, and 100 °C, were observed and found to cause a decline of the failure load with the temperature increment. Further, it was identified that the failure modes and the patterns of the CFRP/concrete samples also changed with increasing temperature. Further, it showed more elastic failure on higher temperature ranges and showed more brittle failure at low temperature ranges. Due to softening of the polymer adhesive, at 40 °C the CFRP/Concrete specimens showed a cohesive failure [2].

Generally, resins are divided into two main groups: thermoset and thermoplastic. Thermosetting polymers are commonly-used for structural applications, like concrete retrofitting with CFRP Fabrics, because they make strong bonds with many substrates [14]. Depending on the type of adhesive, most thermosetting adhesive polymers get cured in the room or at higher temperatures. This curing process can be identified as an irreversible chemical reaction that generates heat due to an exothermic reaction that occurs during the curing process and due to this heat, the process called cross-linking takes place. By providing additional heat externally, it can increase the curing temperature of the specimen beyond the initial glass transition temperature of the used polymer adhesive, which increases the physical mobility of the moieties and is chemically active. Hence this additional heat helps to the continuation of subsequent cross-linking and become a more stable state [16].

1.2 Research Scope

The scope of conducting present research is to study the behavior of elevated temperature cured CFRP specimens under different service temperatures. As a result of focusing on CFRP strengthening technology, in the construction industry, many researchers have been performing their research studies to find the behavior and properties of the materials, which are used for strengthening concrete. Most of the researchers have focused on the behavior of the bond of resins and the substrata. Some researchers have carried out their studies to find the behavior of bonding of the CFRP/Concrete under various environmental conditions [2, 9, 10, and 11]. In the literature survey, it was found that one of the researchers commented on the behavior of CFRP strength specimens which, cured under solar radiation [4] and another commented on adverse impacts of high-temperature curing of the CFRP/Concrete bonded specimens over 100°C [9]. However, none of them focused on the behavior of samples, which cured at elevated temperature, slightly higher than the glass transition temperature of the adhesive. Therefore, the author identified the gap and conducted the experiments to recognize the results of the behavior of bonding of the CFRP/Concrete specimens which cured at a slightly higher temperature, than the glass transition temperature of the adhesives used for the strengthening of the specimen.

1.3 Research Objectives

Identify the behaviour of bond strength of the available epoxy adhesive commercially, which used in CFRP/concrete strengthening, which cured at a slightly higher temperature than its glass transition temperature.

1.4 Summary

The studies carried out in this document explore the application of elevated curing temperature for an epoxy adhesive, which is commercially available, used for CFRP/concrete strengthening. Under this study, elevated curing temperature regimes were applied on the CFRP/concrete specimens for an initial selected period of time and then allowed to cure at ambient temperature. The bond strength was examined for both ambient and elevated temperature conditions. Observations of this research study may deliver the instructions for practices and methodologies for the strengthening of structures in exterior situations to maintain the designed strength in an elevated temperature environment.

02. Literature Review

2.1 Introduction

CFRP/Concrete strengthening is widely used in retrofitting existing structures due to various reasons. FRP materials provide several advantages over conventional steel which mostly used for retrofitting of civil structures, among them: (i) high tensile strength to the self-weight ratio (ii) less weight, hence easy to handle and less dead load added on the structure, (iii) corrosion resistance property provides high durability when subjected to aggressive environments, (iv) low coefficient of thermal expansion, (v) due to electromagnetic neutrality and high flexibility in sizing, can be used in a wide range of structures and (vi) flexibility to form any shapes [19].

Usually, the bond between CFRP/concrete is achieved using structural epoxy adhesives. Generally, it can be defined as the transferring of stresses from concrete to the layer of CFRP while providing a continuous connection among the concrete and the layer of CFRP. Composite action of the CFRP/Concrete specimens are achieved by using shear stress transmission through the film of the adhesive layer formed in between the concrete and the CFRP fabric.

The main disadvantage of the polymer adhesives, which is used for the construction industry, is getting weak during the elevated temperature. In most of the countries, the mid-day temperature of the outer surface of the structures, which are exposed to direct sunlight, increased around 45 ℃ - 60 ℃. This temperature is very near the glass transition temperature of the epoxy adhesive. Glass transition temperature (T_g) can be defined as the temperature which undergoes physical property variation of the polymer from plastic to crystalline [2]. To investigate the findings of previous research projects carried out, by many experienced researchers, to recognize the effects of the glass transition temperature on the bond of CFRP/concrete, an enhanced literature review was carried out by the author.

Most of the works of literature are based on non-experimental methods by modeling the scenarios using finite element modeling (FEM). They have used some sophisticated software that can carry out FEM modeling and to generate the meshes and get the final data. To simulate the data, researchers used experimental data carried out on their own studies and results of past research studies available. To investigate the bond behavior of CFRP/Concrete specimens on various temperature conditions, a few researchers have undertaken laboratory investigations due to difficulties to arrange the environment to simulate actual conditions in the laboratory.

2.2 Detailed literature review

There were several experimental and theoretical kinds of research studies carried out to investigate the behavior of CFRP/concrete bonding under elevated temperature in the last few decades. Few research studies were performed to investigate the impact of post-curing techniques on the bond behavior of the CFRP/concrete specimens. Very few studies were performed to investigate the influence due to elevated temperature curing of the polymer used for CFRP/concrete bonding. The outcomes of such investigations are summarized under the attributes given below.

2.2.1 The testing methodology of the bonding system

In the research literature, several types of tests, carried out to evaluate the properties of the bonding layer among the CFRP fibre and the concrete. The selection of testing methodology depends on the simplicity of the testing procedure, the easiness of load application, the smaller size of samples, and the lower rate of expected deviations in the results [1]. Commonly carried out tests to identify basic bond properties for the bonding systems is the shear-lap test [16]. There are two types of shear lap tests that are popularly used for testing. One of the test setup is known as single-lap shear test and the other test setup is known as double-lap shear test. To assess all intermediate stages of loading up to failure and to monitor the changes continuously on the material face during different stages of loading the single shear lap test can be selected [1]. The advantage of a single shear lap test is that it required only a lesser amount of material and fewer concrete blocks. In the double shear lap test, two faces loaded with shear the loading effect and involved in the process according to weaker bond due to poor workmanship. The advantage of the double-lap test is less the probability of eccentric loading and lesser deviations in ultimate load can be achieved [1].

Most of the research studies, conducted by the investigators, the single shear lap test had been used to identify the bond properties for elevated temperature [10], to identify effects of cyclic temperature changes [11], to identify effects of mechanical stresses [11] to identify post-curing effects [2] and to identify the combined effects [9].

Similarly, some of the researchers had used double shear lap tests for their experimental investigations to find bond properties at moderately elevated temperatures environments of the bonds between CFRP/Concrete [8] and CFRP/Steel bonds [15].

Different sizes of the concrete specimen were selected by each researcher, for their studies. As an example, some of the researchers have used 130 x 130 x 300 mm size concrete blocks for their studies [10], while some other researchers used 75 x 75 x 250 mm size concrete blocks [2, 9, and 11]. 120 x 120 x 350 mm size concrete blocks were used by Frimo [8] under double shear lap testing and 75 x 75 x 240 mm concrete prisms used by Al–Tamimi et al. [4] for their studies.

Strain variation during the single shear lap test was measured by optical measuring technique [11] and three dimensional non-contact image correlation technique (photogrammetry) [9].

The study was carried out by Al–Tamimi et al. [4] to investigate the stability of the bond between the concrete/ CFRP specimens, when they are exposed to severe environmental conditions. During the study, the researcher perceived that the specimens which opened to the direct sun rays during the summer period (peak temperature of each specimen varied in day time ranges 38°C - 55°C during the summer), showed a growth in the bond strength as well as in achieved peak loads. Introduction of the epoxy interface, to the elevated temperature, showed increments in the bond strengths due to greater cross-linking of the applied polymer, by forming complex collaborations in the polymer matrix [4].

To find characteristics of CFRP/Concrete bond, most researchers had tested the strengthened specimens, in two ways. They are; (a) steady-state tests, first heated the specimens to pre-defined temperature then loaded till it reach failure; and (b) Transient tests, first loaded up the specimens to pre-defined load using mechanical anchor which contains spring system and the then heated up in constant rate in a furnace till failure [8, 10, and 11]. In the test carried out by Frimo [8] under steady-state test, predefined temperatures were 20°C, 55°C, 90°C and 120°C. Li et al. [15] investigated the consequence of the temperature increments on bond behavior, using CFRP/steel specimen, by considering temperature as the only variable, used the temperatures; 27 °C, 40 °C, 50 °C, 60 °C, 80 °C, 100 °C, and 120 °C for the studies. Application of varying load in an oven has done the researchers using a closed-loop loading system [12].

2.2.2 Surface Preparation

Generally, retrofitting of the structures using CFRP, carried out as an external strengthening system. The popular bonding system used for this type of strengthening is the wet lay-up method. This is mainly due to the easy application, flexibility, and can follow any complex geometric shapes. The use of improper application methods of CFRP, curing, and use of poor surface treatment before application of adhesive may cause weaker bonds [1]. Hence good workmanship, as well as better knowledge in practical application, is important.

Adhesives are acting as the bonding agent between two surfaces; concrete and the CFRP. Other than characteristics of the epoxy the surfaces, which are supposed to attach, must be prepared suitably. Hence to achieve proper bonding, the concrete surface has to be prepared specially. For an ideal bonding of these surfaces, some of the criteria of surfaces must be satisfied. They are (a) cleanliness of the applied surface, (b) continuity of the material applied, (c) stability of the different material applied, and (d) proper wetting of the surface by the adhesive [11]. To achieve the above-mentioned criteria, several types of surface preparation methods were adopted by researchers. These methods can be categorized under mechanical or chemical surface preparation. Under mechanical methods of surface preparation; shot blasting, sandblasting, incrustation, scratching, grinding, or subjecting to high-pressure water jets are popular among researchers [12]. Under surface preparation, the concrete blocks were sandblasted to take away the cement paste and uncover the coarse aggregates of the concrete to achieve proper bonding [2, 9, and 11]. Use of high-pressure water jets for the preparation of surfaces of concrete specimens were carried out by few researchers [10]. Before application of polymer or primer, the concrete surfaces were brushed for further cleaning and to remove any free dust particles [9, 10, and 11].

The prepared surfaces of concrete specimens consist of valleys and crevices. At the application of the adhesives directly on such surfaces, due to relatively higher viscosity, the polymer runs into the depressions and perforation on the concrete surface, creating adhesive associations with the depressions formed on the surfaces [7]. Most of the adhesives used by the researcher's results only limited bonding for the most of the used substrates, which was caused due to the less surface energy of the cohesively weak coatings [1]. Primers work to enhance the ability of adhesion, in these kinds of situations, this action is known as wetting, and the primer layer usually acts as bi-functional material by providing improved interfacial characteristics and proper bonding to both the substrate and the adhesive [11]. Hence quick application of the primer layer carried out just after surface preparation by the researchers [9, 10, & 11].

2.2.3 Method of monitoring the temperature

Monitoring the temperature of the epoxy interlayer is very important, for the researchers, because most of them monitor the behavior of epoxy adhesive under elevated temperature curing and/or finally test under pre-decided elevated temperature. Most of the researchers were used to embed one thermocouple in the epoxy interlayer. Such thermocouple requires to be small in size/diameter and should be able to connect to a data tracker to measure the temperature. It is noted that most researchers used a data-tracker to increase accuracy of the temperature measurements and it takes measurements in 1-second intervals confirming the precision [12]. Type "K" thermocouples were attached to the data-tracker for the purpose of measuring the temperature distributions in the adhesive interlayer at elevated temperatures [9, 10, & 11].

2.2.4 Effect of Glass Transition Temperature on bond behavior

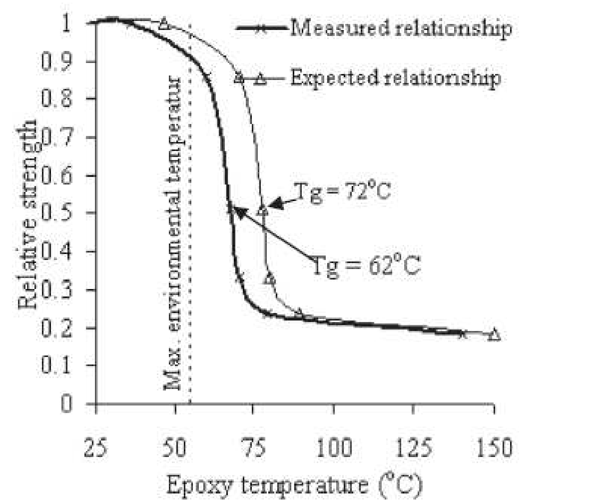

Figure 1. Relative strength vs. epoxy temperature.

The durability of CFRP/Concrete bond systems may also be affected by extreme environmental temperatures because of the continuing conversion of matrix from hard status to an elastic status at high temperatures [4]. The glass transition temperatures (T_g) of most construction adhesives are relatively low and can be cured at ambient conditions [12]. Such cured epoxy polymers initiate to depreciate the material parameters of the bond line around the temperature 10 °C lesser than T_g of the polymer adhesive, at the range between 40 °C and 55 °C of temperature[10]. For the studies carried out to find the outcomes due to temperature escalations closer to T_g on the bond parameters, using CFRP/steel specimens, the thermal exposure showed decrement in the stiffness and ultimate load carrying capacity of the specimens, mainly at temperatures that closer to T_g of the polymer adhesive [15]. The author further mentioned that the adhesive interface between CFRP and Steel substrates behaves as a weak connection and the major detected failure mode was de-bonding [15].

At altered persistent elevated temperature levels, a sequence of single-lap shear tests was carried out by the Gamage et al. [4] using CFRP strengthened concrete blocks and plotted the relative bond strength vs. temperature. The chart extracted from the literature exhibited that the sensitivity of link between CFRP/Concrete, to the temperature escalations and enormous strength decline was shown closer to the glass transition temperature, in the temperature ranges between 55 °C – 65 °C (Fig. 1). The glass transition temperature of the adhesive was shown as 62 °C for the measured relationship [16]. The properties of the polymer used showed quick depreciation closer to the glass transition temperature of the used polymer, due the process called molecular mobility at the glass transition temperature of the polymer [7].

By improving the glass transition temperature of the bond medium, it can minimize the process of molecular mobility of the polymer and increase the stability of the bond, for the high-temperature atmosphere [9]. Curing with elevated temperature will increase the glass transition temperature of polymer adhesives [16].

Gamage et al. [9] has given the effort to develop the glass transition temperature of the polymer adhesive interface of the CFRP/Concrete bond. For this, the variations of the characteristics of pure epoxy adhesives, due to elevated temperature curing at the glass transition temperature were observed. The measured values displayed a 10 °C increment of the glass transition temperature of the pure adhesives, for the both high temperature cured specimens for 5.5 h and post-cured specimens, when compared with ambient temperature cured samples.

It was expected that the increment of bond performance with the increment of the glass transition temperature of the adhesive was the effect of post-curing, which is shown by Fig. 1. The curing at room temperature as well as under different curing conditions were used for this study. Graphical representation of the viscous modulus vs. temperature, is shown in fig. 2 for the specimens that cured at high temperature, which tested for both short-term and long-term performance, as well as post-cured specimens at 100 °C & 150 °C for 5.5 h period. Further the short- and long-term effects due to high-temperature cured & post-cured systems at 100 °C for 20 h also showed in the above graph [9].

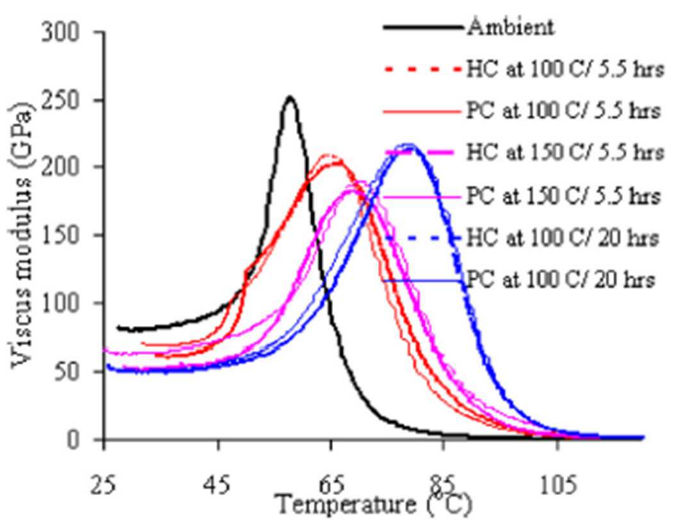

Figure 2. Effects of curing on T_g of epoxy.

HC – Elevated temperature cure (curing at 100 °C just after preparation).
PC – Post-cure (curing at 100 _C after being fully cured at ambient conditions).

2.2.5 Effects of post-curing on adhesive/resin and bond strength

The influence of post-curing temperature on the bond behavior was analyzed in several studies. Most of these were carried out as experimental studies using CFRP bonded concrete specimens. Under increasing temperature, used epoxy polymer adhesive for the purpose of bonding among concrete and CFRP fabrics, is very sensitive to temperature and deteriorates the properties of the adhesive rapidly [10]. Hence, the target of these studies was to advance the glass transition temperature of the epoxy adhesive and get lesser vulnerability of bond strength against the harsh environment with elevated temperature.

Post-curing comprises the temperature treatments, which are applied on the epoxy layer of the CFRP/ Epoxy bond, after its initial curing period of 7 days, to get maximum cross-linking and T_g and improved physical characteristics [16]. Few research studies have been undertaken to explore the improvements in CFRP/Concrete bonds using commercially available epoxy adhesives [2, & 9].

The study was carried out by Al-Safy et al. [2], to monitor effects of the adhesive properties, by application of high and the moderately elevated temperature post-curing as specified operating conditions. Under this, the bond efficiency of CFRP/concrete systems, the behavior of T_g, modulus, and tensile properties of adhesives were monitored at elevated temperatures [2]. At the comparison carried out using the specimens, which cured under ambient temperature conditions, it was observed that the failure loads for post cured specimens were very low and identified 20% short-term strength reduction in the CFRP-strengthened specimens, which is exposed to high temperature post-curing at 100 °C for 5.5 h. It was identified that the substrate failure is the reason for this strength reduction due to high temperature. It was argued that this happened due to micro-cracks formed in the concrete substrate due to rapid evaporation of moisture in high temperature, which creates the weaker mechanical properties of the substrate. Similarly, it was assumed that due to this weaker substrate the system failed at a lower load level. In the presence of moisture, a higher failure load was recorded for the elevated temperature curing [9]. Similar observation recorded by Al-Safy et al. [2] and explained that even though there is an enhancement in the temperature of debonding in the range of 8 °C – 9 °C and significant improvement in T_g, for post-curing high temperature, but negative impact is shown for overall bond strength as a result of development of micro-cracks on the bond line. Exposure of high temperatures (at 100 °C and 140 °C) as post-curing, showed improvements in the tensile properties of epoxy adhesives. It showed enhancements in both the tensile strength and tensile modulus and ductility than ambient temperature cured samples for the specimens, which were tested under ambient temperature, 40 °C and at 60 °C.

Another research study carried out by Stewart et al. [18] testing of materials, to find the cohesive performance of an epoxy adhesive as a function of post-curing duration and temperature. These tests were carried out under tensile loading conditions, compressive loading conditions, and flexural loading conditions. Monitoring of these tests were carried out using electron microscopy techniques for the purpose of understanding the adhesive performances.

The adhesive material was initially cured for 24 hrs under ambient temperature and then subjected to three curing temperatures and three durations to get nine possible post-curing exposure conditions. The variation of the glass transition temperature of epoxy against post-curing duration and the post-curing temperature is shown in Figure 3 & 4 respectively.

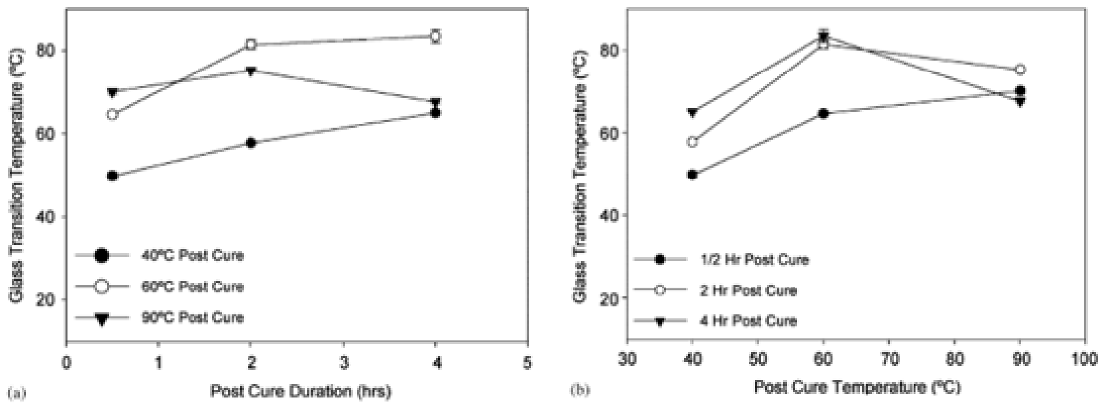

Figure 3. The relationship between glass transition temperatures to post curing

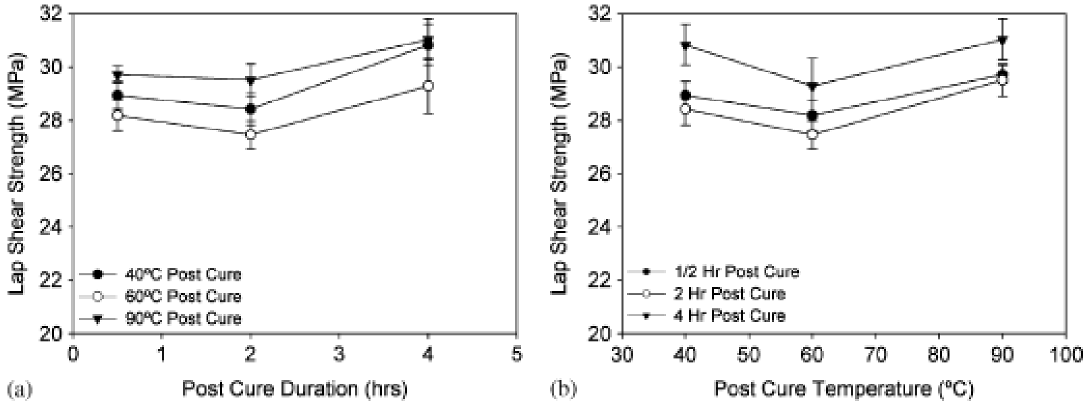

Figure 4. The relationship between lap shear strength variations to post-curing

According to the sample, which post-cured with 60 °C shows better improvement for a period of 2 hrs and 4hrs post-curing. For the sample, post-cured with 90 °C, deteriorates the glass transition temperature with a longer duration than 2 hrs. The researcher mentioned that, when the material is cured at 90 °C for 2 hrs, the lap shear strength of the adhesive is also reduced, but it shows higher shear strength for both ½ hrs and 4 hrs curing period. However, 4 hrs post-curing gave the highest shear strength value for the epoxy adhesive used. This showed that increasing the chain stiffness requires high energy input for a longer time to create the polymer links to mobile easily achieving superior cross-linking, with a greater glass transition. This indicated that the degree of cure can be considered as an extremely significant concern in the practical applications of the structural epoxy adhesives [18].

The study was carried out by Al-Safy et al. [2], to find thermo-mechanical behavior of few polymer adhesives, which applied for preparation of CFRP/concrete specimens using post-curing techniques. With the results received the researcher observed that the controlled specimens, which are not subjected to post-curing, tested at 60 °C, approximately 47% of the decline was encountered compared to the specimens, which were not subjected to post-curing, and tested at ambient temperature environment. Further, the researcher noticed a 57% of reduction of the ultimate failure load, for the post-cured samples, at 60 °C Similar to above criterion, it was observed the declining behavior of the ultimate failure load as the service temperature increases and for the post cured samples, 8% reduction in ultimate failure load was recorded [2].

A 20% reduction was recorded by Gamage et al. [9] for the short-term strength of CFRP/Concrete specimens, which were subjected to 5.5 hrs. post-curing at 100 °C, compared to the ambient temperature cured specimens. The micro-cracks were developed in dry concrete at high-temperature post-cure and weaker bond strength of CFRP/concrete bond was recorded, for high-temperature cured specimens, when compared with ambient temperature cured specimens. Hence the researcher argued that the adhesives, which are manufactured for the ambient temperature curing, are not recommended for elevated temperature exposure to either during or after the curing process. Hence the researcher is not recommended to carry out high-temperature post-curing for the CFRP/concrete system [9].

2.2.6 Effect of elevated temperature curing on adhesive/resin and bond strength

Post curing has a major disadvantage even though it increases the glass transition temperature of epoxy adhesive which is used for CFRP/Concrete strengthening because it has to be carried out after completion of the normal curing process under ambient temperature for seven days. In practical applications, due to time constraints in the real construction environment, carrying out post-curing is getting unpopular.

To overcome this time constraint, the elevated temperature curing has been proposed by Gamage et al. [9] and that was carried out as part of her study to find effects of long-term cyclic temperature and mechanical stress on CFRP/concrete bonds. Under this researcher cured few specimens, which strengthen with CFRP fiber using the wet lay-up method, under elevated temperature curing to find bond behavior against elevated temperature curing. Curing was carried out by placing the specimens in an oven directly after the fixing of CFRP fiber, for 5.5 h period, at 100 °C persistent temperature, and the balance curing period, the specimens were preserved in room temperature condition. Then the specimens were tested for mechanical stresses at long-term temperature cycles. By analyzing the results received, the researcher forwarded an argument mentioning that there was the deterioration of bond properties, with elevated temperature more than 100 °C curing just after installation, even though elevated temperature curing, which helps to improve physical characteristics of epoxy adhesives, by improving cross-link density and Tg. [9].

However, to assess the exposure to the harsh environment, one set of the specimen was directly exposed to the sun, by Al-Tamimi et al. [4], during summer time, which ranges the temperature between 38 °C and 55 °C for a three months period as a post-curing technique.

2.2.7 Effect of sustained load and cyclic temperature on adhesive/resin and bond strength

The specimens strengthened by Gamage et al. [9] with CFRP had subjected to service loads, varying from 0% to 35% of the applied load at the ultimate failure of the controlled samples for 1800 hrs., and 2250 hrs., while subjected to cyclic temperature ranges 20 °C - 50 °C in a programmed furnace, before testing. According to the results received, the researcher, recognized that the 25% loaded specimens indicated the best performance as shown in fig 05. The reason behind this was elastic forces of epoxy start to relax slowly once the resin is exposed to constant and lower strain conditions. Hence this researcher argued that the residual strength of stressed specimens with low stresses improved than unstressed specimens [9].

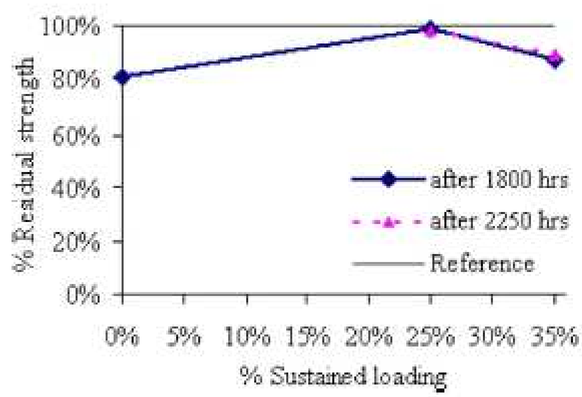

Figure 5. Residual strength vs. sustained loading

2.2.8 Failure loads

Different failure loads were recorded by different researchers for controlled specimens. This might be due to various reasons like selected bond length and width of the fiber strip, which is used for strengthening the specimen and type of adhesive used.

The failure loads for controlled specimens, on the research study tested for short-term strength of CFRP at ambient temperature, were considered as 100% strength by most of the researchers, and strength variations due to various reasons were shown as either percentage increments or percentage reductions concerning the failure loads for controlled specimens. With the increment of testing temperatures, reductions in failure loads were recorded [7]. A similar observation had been recorded strengthening the above observation, by most of the other studies [1, 9, 11, & 12].

When specimens were subjected to cyclic temperature effects ranging from 20 ℃ -50 ℃ for a longer period without sustained load, the 20% reduction in failure load was recorded. This reduction minimizes when specimens are subjected to sustained load while applying cyclic temperature effect and found maximum regain of strength by specimens subjected to sustained loading of 25% of failure load of controlled specimen [9].

The specimens, who exposed to the direct sun in summer, which ranges the temperature between 38 °C and 55 °C for three months period and under 15% and 25% sustained loading, achieved 25% increment in average peak loads [4], compared to failure load of controlled specimen tested at ambient temperature [1].

It showed a 9% increment in the ultimate failure load, for the CFRP/concrete samples which post cured at 60 ℃ which specified as moderately elevated temperatures, for 4 h, compared to the ambient temperature cured samples [2].

At the comparison of the specimens, against to the ambient temperature, cured specimens, a 20% decline in the short-term strength was recorded by Gamage et al. [9] for the specimens, a strengthened using CFRP and exposed to 5.5 h time period of post-curing and elevated temperature curing at the constant temperature of 100 ℃. The explanation given by the researcher for this failure load reduction was the micro-cracks developed in dry concrete as a result of high temperature. Further, the researcher urges that the bond strength of CFRP/concrete specimens showed weaker behavior for high-temperature cured specimens, than the ambient and post-cured specimens. Hence the researcher is not recommended to carry out both high-temperature curing and post-curing for the CFRP/concrete specimens. However, the researcher proposed to carry out detailed investigations, to assess operable post-curing temperatures, by application of different temperature levels and curing periods for the specimens in a way to achieve optimum performances without damaging the substrate properties. However, strength regaining was observed by a researcher for the specimen who, conditioned without sustained load, after post-curing. The longer conditioning period showed more recovery of strength [9].

Further, Gamage et al. [10] recognized that the strength of the bond between CFRP/concrete disappeared when the temperature of the epoxy interlayer reached around 70 - 81 °C as the experimental results and 70 - 76 °C as the numerical results. According to the results of the research, the author mentioned that, at elevated temperature, the adhesive temperature was identified as the main influencing factor for the loss of strength of the CFRP/concrete specimen and it is independent from the bond length [10]. Hence in case of fire, it is a mandatory requirement to provide fire protection applications encompassing the CFRP strengthened members to preserve the link among the CFRP and concrete materials.

2.2.9 Failure mechanism during single shear lap test.

The various failure modes which accompanied the single-shear lap test were identified by the Pham et al. [16] as per the data found from the literature shown in Figure 6.

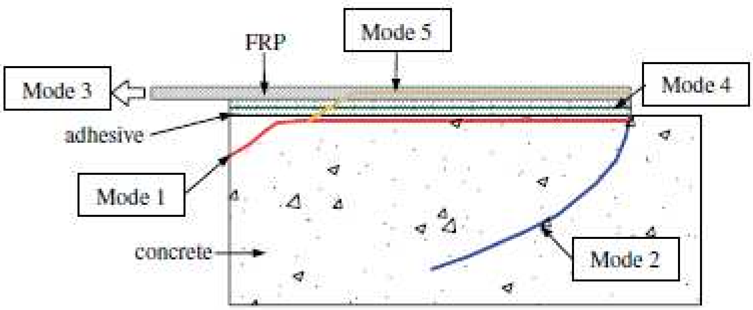

Figure 6. The Observed Failure modes during shear-lap tests [16].

The details of above showed failure modes are given below;

Mode 01 - Interfacial debonding failure, Pharm identified this as the most common failure mode, in which the failure surface runs in concrete parallel to the bonding surface.

Mode 02 - Shear tension failure, this failure mode occurs when the laminate is relatively thick and crack develops from the FRP end into the concrete block.

Mode 03 - FRP tensile rupture failure, occurs when there is a small cross-sectional area of FRP.

Mode 04 - Cohesion failure, this failure happens along the layer of polymer.

Mode 05 - Delamination of FRP composite, this failure route goes into the concrete through the adhesive layer.

Most of the other researchers also followed similar failure identification in their research studies.

Under ambient conditions, the failure pattern observed in CFRP/epoxy/concrete specimen is concrete fracture failure [9, 11]. Hence, the properties of concrete can be considered as the critical factors for this bond failure and it can happen at the elevated temperature, as a result of short-term influence [9, 11]. Similarly, concrete rupture failure observed for the specimens subjected to cyclic temperature effects ranging 20 °C - 50 °C for a longer period with up to 25% sustained load, indicating better bond than substrates. The outcomes of the test showed that the failure criterion of the specimens transferred from concrete rupture failure to pure interface failure with increased sustained loading, for both high and low viscous adhesive. The observed strain distributions were similar, along the bond line of the both control specimens and conditioned specimens for the low level of sustained loading. The researcher further highlighted that, similar failure modes and strain distributions were observed for specimens trained for both 1800 h and 2250 h indicating that, the deterioration of bond properties are not depending on the conditioning period [9]. A similar type of observation was recorded by Lai et al. [14] due to not seeing significant differences in thermo-grams and the strength data obtained from the three studied periods of 5-week, 15-week, and 30-week exposure periods.

The complete bond failure was recorded as the combined influence of 20 to 50 °C temperature progressions, and 90% humidity, for higher continued loads. This failure mode is observed within a comparatively short number of cycles [11]. Similarly, Edward [7] also experienced for the specimens exposed to elevated temperature for the short-term period, as a result of increased molecular movements of the polymer adhesive initially, and showed increment of toughness of the polymer while declining of cohesive stability. Pure bond failure was observed with a higher number of cycles of exposure and combined minor concrete fracture and interface bond failure mode was observed with an intermediate number of cycles [11]. Similarly, pure bond failure was observed in the specimens, who had been exposed to cyclic temperature progressions, while providing high humidity conditions and the stresses, in a shorter period [9].

A sudden de-bonding failure was recorded by Al-Tamimi et al. [4] for the specimens, which were exposed to sun and saline environments. In this debonding, it was observed as an explosion indicating that the polymer layer was enhanced, its strength due to direct exposure to the sun in the summer period [4].

For the specimens which tested at 60 °C, it was monitored a flaking off failure of the CFRP layer, and for the lower temperatures (less than 50 °C) showed a mixture of bond failure and the failure by concrete rupture [12].

Four stages interfacial cracking and debonding was identified, during the series of test carried out to develop infrared thermography methodology, to explore the combined influences of the water intrusion and exposure to elevated temperatures on the externally-strengthened CFRP-concrete specimens, who immersed in different water baths which heated at various temperature levels (25 °C, 40 °C, and 60 °C) for a period of 5, 15 and 30 weeks, namely: a). Elastic stage (either interfacial softening or separations are not visible on the entire bond line), b). Elastic-softening stage (at the loaded end, unstiffening of the polymer starts locally while some portions of the interfacial bonding layer become softened near the fixed end while it remains elastic). c). Elastic softening/de-bonding stage and d). Softening/de-bonding stage (separation of the bond layers occurs locally and it broadcasts from the loaded end towards the fixed end) [14].

2.2.10 Interfacial Bonding Characteristics

Epoxy adhesive polymer, which is generally used for bond between concrete and CFRP plates or fabrics, are very sensitive against the environmental temperature variations. Under increasing temperature, properties of Epoxy adhesive polymer deteriorate quickly [10] and adversely affect the CFRP-concrete bond strength. An 8% drop in the ultimate failure capacity showed for the samples, which cured at ambient temperature, tested at 40 °C, when compared to the similar specimens, which tested at ambient temperatures conditions [2]. However, when a specimen is exposed to a moderate temperature for a long time improves its failure strength significantly. This was observed by keeping the specimens under the direct sun in summer for three months period, which, exposing natural temperature cycle ranging between 38 °C and 55°C and predefined sustained loading condition, showed 20% improvement in its strength [1].

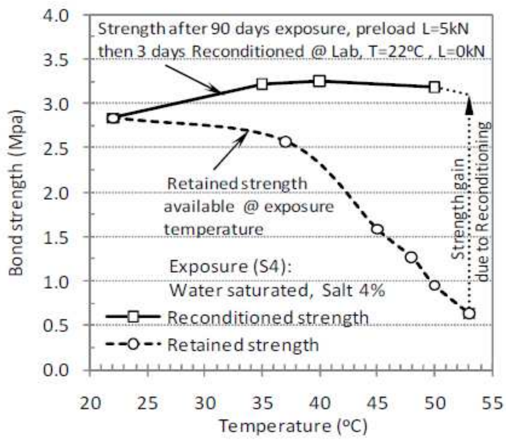

Figure 7. Effects of temperature on reconditioned and retained bond strength

Similar consequences of bond strength outcomes were monitored by Pham et al. [16] during his study of CFRP-concrete shear-lap tests, which are similar to above. Under the first consequence, increasing the temperature towards T_g may reduce the bond by modifying the adhesive status to become more plastic. As a second consequence, the high temperature enhances the properties of the adhesive within the curing process, enabling it to achieve a better bond between the CFRP and the concrete surface. Those effects clearly showed in Fig. 7. The solid line represents the reconditioned bond strength of preloaded samples which were tested after relief of the load and 3 days of the reconditioning period, tested after at 22 °C and showed an increment in bond strength with temperature from 22 °C to 40 °C. Hence the researcher argued that only reconditioned samples were improved by the temperature of curing for the range of exposure temperatures tested [16].

As per the above observations, either post-cured or elevated temperature cured specimens with slightly elevated temperature showed enhancement of T_g of epoxy due to better cross-linking. However, as per the study carried out by Gamage et al. [9], either cured at higher elevated temperature or post-cured at higher temperature was not succeeded due to micro-cracks formed in the concrete substrate. For this, the researcher compared the specimens both post cured and elevated temperature cured specimens, which subjected to elevated temperature curing or post-curing at 100 °C temperature for the period of 5.5 h and observed a 20% strength reduction in both post-cured or elevated temperature cured specimens than the specimens cured under ambient temperature conditions.

2.2.11 Strain distributions over the bond length.

It was observed that the non-linear strain distributions, for CFRP/concrete bonded interfaces, at ambient temperature, while strain distributions for elevated temperature were closer to linear. This behavior of polymer showed due to stiffness reduction and as a result of smoother shear stresses developed at the bonding face [8]. The adhesives used by Gamage et al. [9], were formulated for ambient temperature curing. The samples exposed to the similar conditioning patterns of the ambient, high-temperature cured and post-cured systems exhibited equal patterns of strain development along the bond line. The failure happened along the boundary of adhesive and the CFRP layer. However, the researcher indicates that there was a deterioration of bond properties, which was subjected to 100 °C elevated temperature curing and post-curing as well [9].

The effective bond length was increased consistently with the increments of the testing temperature. Much lesser bond length was observed at ambient temperature than the specimens, which tested at 55°C and exceeded the bonded length observed at 90 °C and 120 °C. Further, it showed a continuous and significant reduction of the bond strength as a result of the undergone glass transition process at the elevated temperature of the epoxy adhesive layer [8].

The specimens subjected to cyclic temperature effects ranging 20 °C - 50 °C for a longer period, showed 80% of strain distribution for the specimen which was subjected to 0% sustained loaded specimen, and 30% of strain distribution observed for the specimen which subjected to 25% sustained load specimens. Further, this showed that 15% strain distribution for bond length near the loaded edge for the specimen loaded 35% of sustained loading, but this was relatively lower strain than unstressed specimens. However, the samples, which are exposed to the similar conditionings, in ambient, high-temperature cured and post-cured, environments exhibit much similar strain distribution patterns [9].

2.2.12 Areas of concern and research needs

Most of the past studies carried out by researchers, conducted investigations to identify the behavior of CFRP/concrete bonds in elevated temperature environments and found more valuable points regarding the bond strength at the variation of temperature from ambient to higher levels [4, 8, 9, 11, 12, & 15]. Few of the researchers carried out the effect of post-curing for the CFRP/Concrete bond and some of them were not recommended to use high-temperature post-curing for CFRP/Concrete bond strengthening as a result of the development of micro-cracks in the concrete substrate due to high temperature [9]. However, the application of moderate temperature for post-curing is recommended by some of the researchers [4].

Most of the research, done for elevated temperature, was carried out in an oven to maintain the constant temperature during the testing period. However, the application of incremental loading is not very practical in such an oven, to overcome this issue, either the oven has to be modifying suitably or uses an advanced system like a closed-loop loading system [12]. With available testing equipment, most researchers use a constant loading system, using springs and frame, for their studies. Hence experimental data for bond strength at elevated temperature could not be found. Hence this figure has been predicted using either mathematical expressions or using graphical interpretations.

Gamage et al. [9] highlighted the importance of exploring the bond behavior of CFRP strengthened specimens, at severe environmental surroundings and improving the knowledge of the behavior, before practical applications for the outdoor structures in such severe environmental conditions [9]. Due to not recommending the high-temperature curing to improve the T_g of an epoxy adhesive for the CFRP/concrete system, it needs to find a suitable range of heating for better performances without damaging the concrete substrate.

Hence this research study concentrates on the application of elevated curing temperature for an available epoxy adhesive commercially, which can be used for the connection of the CFRP/concrete strengthening systems. Under this study, the author developed a suitable arrangement to simulate the application of elevated curing temperature regimes to the CFRP/concrete specimens, while application of incremental loading, without using an oven. The effectiveness of moderately elevated temperature curing on bond strength was studied, under this experiment, for both ambient and elevated temperature conditions. The finding of the study may be useful for improving methodologies for strengthening outdoor structures to maintain the designed strength in an elevated temperature environment.

2.3 Summary

Concrete retrofitting with CFRP technology is the most overwhelming methodology used by most of the parts of the world. Due to these outstanding uses of the CFRP technology, lots of experimental and numerical research were carried out towards the purpose of investigating the performances of CFRP/concrete connection in the last few decades. Even though such a great number of researches happened in the atmosphere, some gray areas of the behavior of CFRP technology still exist. These not fully uncovered areas can be identified only through a literature review. Hence the author carried out an extensive literature survey to find such a grey area of CFRP/Concrete bonding and was identified that the elevated temperature curing of CFRP/Concrete bonding was not a fully exposed area. Similarly, it was identified that very few research studies were performed towards identifying the influence of post-curing effects on the performances of CFRP/concrete bonds.

With the determination of the gray area to research, the literature review was streamlined to words the identification of the studies towards the targeted area. The finding of the literature survey was categorized into several sub-areas and disclosed in the detailed literature review. Under this, the testing methodologies which were carried out in similar nature researches were observed and identified the sample sizes, which were used in past research studies as well as the sizes of the concrete prisms used for the preparation of the test specimen. Similarly, the methods of surface preparations and the temperature monitoring systems of the inner adhesive layer of the bond, which was used in previous research were also investigated. All the identified information in these sections was useful for the selection of sample size and testing methodology of the current studies used for this research.

Under the observations of past research studies, the effects of Glass transition temperature on bond behavior were identified and similar effects of post-curing temperature on bond strength were also recorded in this section. Effects of elevated temperature curing were also investigated under this section and only found the observations carried out by very few researchers as part of the research studies carried out by them. Further, it was observed that, the effects of sustained loads and cyclic temperature on adhesive bond strength and the deviations of failure load were identified by some of the researchers in their studies. Parallel to these observations, it was identified that the failure mechanisms monitored by most of the research were similar. Further, interfacial bonding characteristics and strain distribution over bond lengths identified by past researchers are also discussed in this chapter.

The detailed literature review carried out in this chapter was given guildline to identify the problem area and finally it was outlined the area of the concern which is going to be covered by the author and its requirement to the industry.

03. Experimental Investigation

3.1 Introduction

This chapter discusses the preparation of test specimens for the experimental program and the sequences of activities that were carried out towards the laboratory testing of the study. It further introduces the material properties, which are used for the preparation of test specimens, both tested and provided by the product manufacturer as per the product specifications. Preliminary investigations carried out to ensure the quality of results is also discussed in this chapter.

For obtaining accurate results, it is very important to follow the proper methodology while carrying out the experimental program. Hence, the experimental studies were carried out under the relevant standards published by the authorized bodies and according to the specifications of the manufacturer. A comprehensive testing program was carried out for the determination of the glass transition temperature of CFRP/epoxy/concrete connection, which cured at ambient and elevated temperature conditions. The curing method implemented by Chandrathilaka et al. [6] was used here as an elevated temperature curing procedure of the CFRP/epoxy/concrete bond, since this method can be easily adopted for civil engineering applications. A total of twenty-five CFRP/epoxy/concrete single lap shear specimens were prepared. While some of them were tested under ambient temperature conditions, the others were tested at elevated temperatures to evaluate the bond behavior, when the system is exposed to environmental temperature fluctuations or fire conditions.

3.2 The framework of the Study

3.3.2 Material properties

Before entering the experimental procedure it is required to identify the materials, which will be used for the research. With the selection of the single shear lap test as testing methodology, the author has identified CFRP materials, which are popular in the construction industry for strengthening. With the ease of availability, the author has selected a commercially available CFRP fabric and epoxy adhesive for the research. The concrete specimens were prepared using the ready mixed concrete supplied to a construction site by one of the ready mixed concrete suppliers. In this chapter, identification of the material properties, which are used for the research, is presented.

3.2.1.1 Concrete blocks

A total of 25 numbers of concrete blocks, which have dimensions of 100 mm x 100 mm x 250 mm were cast using plywood moulds, to prepare specimens under this series of study. These concrete blocks were cast using ready mixed concrete and cured for 28 days by immersing in water, to ensure crack-free concrete and to ensure adequate strength development before further processing [1]. The water/cement ratio of the concrete mix was maintained to about 0.52, in this investigation. Both coarse (10 mm - 14 mm) and fine aggregates were used for the preparation of the concrete mix. Assumed slump was 150 mm and targeted compressive strength at 28 days is 30 MPa. 150 mm concrete cube tests were used to determine the compressive strength of concrete. Compressive strength of concrete test cube was measured for 28 days and it was recorded as 42 N/mm^2 and the standard deviation was 0.2.

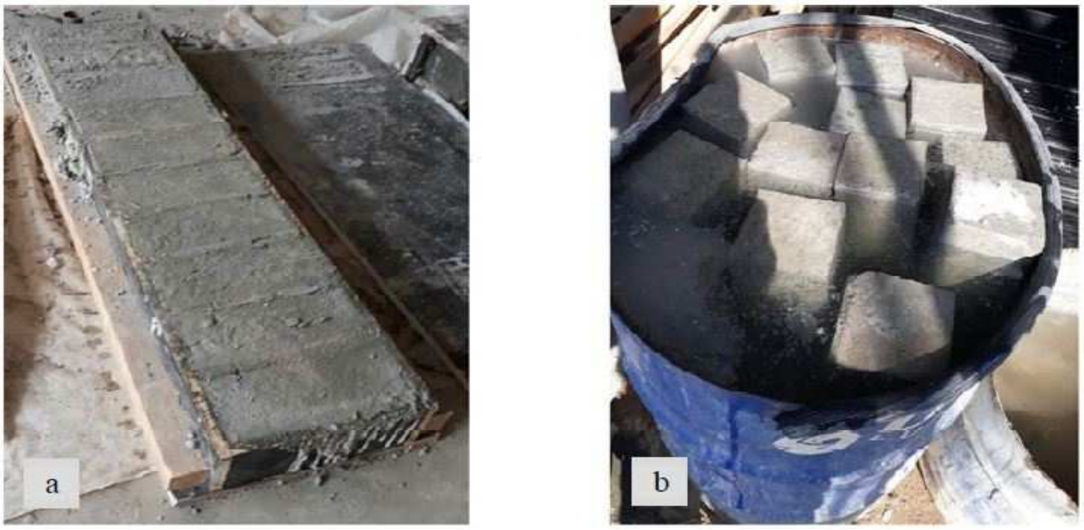

Figure 8. a) Grade 30 ready mixed concrete poured to moulds, prepared using coated plywood concrete blocks, and b) Immersed in water for 28 days for curing

3.2.1.2 CFRP Fiber Fabric

To complete the specimen required for this study, The CFRP strip was taken from fiber fabric, which had the trade name of X-Wrap C300, supplied by X-Calibur Construction Chemistry, US., which arrived as a 500mm wide roll [20]. This fabric was woven in a way to have a unidirectional open weave system, which provides lightweight fabric.

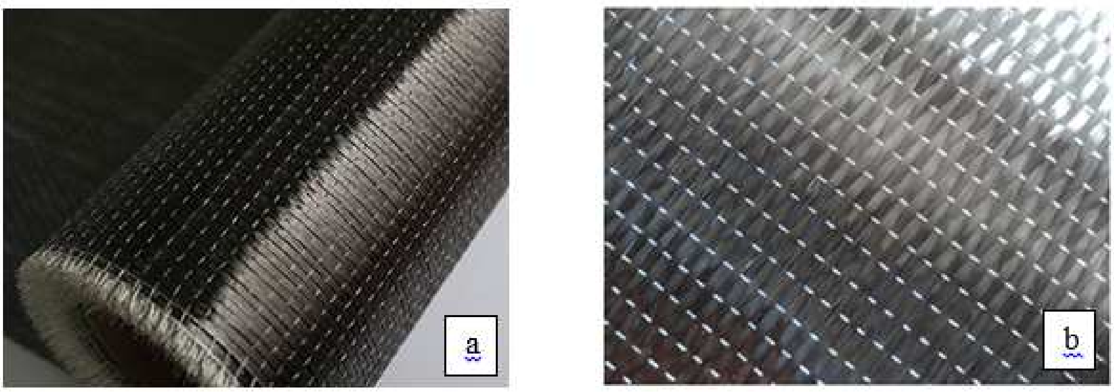

Figure 9. a) 500mm wide CFRP fabric from the manufacturer and b) Closer view of CFRP fabric.

The Manufacturer-provided material properties of CFRP fiber fabric, which is used for the research, are listed in Table 1.

3.2.1.3 Epoxy adhesive

The CFRP fiber fabrics were saturated with the epoxy, having two parts to be mixed together, X-Wrap Lamination adhesive, formulated as a solvent-free, semi-thixotropic system, which was supplied by X-Calibur Construction Chemistry, US [21]. X-Wrap Lamination Adhesive arrived as part A – Base and part B - Hardener and two parts to be mixed thoroughly, just before the application. The Coupon tests carried out for the adhesive were not found. Hence the Manufacturer-provided material properties of epoxy adhesive, which is used for the research, are listed in Table 1.

Figure 10. X-Wrap Lamination Adhesive base and Hardener

Table 1. Material properties provided by the manufacturer

Property of material	CFRP [20]	Epoxy [21]
Tensile strength (MPa)	4000	45
Elastic modulus (GPa)	240	1.67
Ultimate strain	0.02	-
Poison’s ratio	0.3	0.3
Thermal conductivity (W/m.^{0}C)	5	1
Specific heat (J/kg.^{0}C)	1000	1000

3.3.3 Preliminary Investigations

Before starting the laboratory testing, it needed to identify the attributes towards ensuring better results, which were carried out in past studies, as well as much practical and simplest way of testing. This has to start from selecting the size of the concrete specimen. At the testing, it needed to apply variable load while the concrete specimen was subjected to constant elevated temperature. In this chapter, preliminary investigations on bond length, the creation of an elevated temperature environment, which is practically used in the construction industry, and finding solutions to keep the line of the load when testing the specimen in the laboratory were elaborated.

3.2.2.1 Bond length

When preparing concrete specimens, the dimension of the concrete block has to be decided before casting the concrete blocks, to ensure both easy handlings as well as the quality of results. Hence required bond length for the epoxy adhesive was inquired using literature.

Gamage et al [10], mentioned that the nominated bond lengths for the epoxy used in civil engineering construction purposes vary from 75 mm to 175 mm. The same researcher had used 150mm bond length for their studies to find out the performances of CFRP/concrete bonded specimens against the combination of mechanical stresses and long term recurring temperatures [9] with a commercially available epoxy adhesive which recorded lesser tensile strength than the product used by the author. Similarly in this research, the bond length was selected as 150 mm.

3.2.2.2 Elevated Temperature Environment

At the finding of the effect of moderately elevated temperature curing on bond strength of CFRP/concrete bonds, the prepared specimens needed to be cured and tested in a constant elevated temperature environment, and application of variable loading has to be carried out during the test period.

According to the literature, in the past, the researchers used an oven to maintain elevated temperature for the testing specimen, but this was not applicable when it comes to the real construction environment. Hence it needed to find out a methodology to increase the surface temperature of the strengthened concrete elements, which can be used in the construction environment.

The use of radiation heat transferring for this purpose, proposed by the research supervisor, and at the further investigations, it was revealed that the Halogen Lamps with higher wattage and UV lamps, which use in cold countries to heat public areas, also can be used for this. Finally, the method of heating using Halogen Lamps was selected for the studies due to its easy availability in the area and the possibility of practical applications.

3.2.2.3 Application of Variable Loads

Application of load for the prepared specimens at the testing phase was selected according to the resource availability at the laboratory. Universal testing machine with 1000 kN capacity used for the application of loads. When the application of load, concrete block, may tend to skew and skewed loading may cause detachment of CFRP fabric strip from concrete block, without showing its maximum strength. Hence, it is required to maintain the line of load, while application of loading in a way suitable to the clamps of the testing machine. Hence the author has developed an instrument to fulfill this requirement as shown in Figure 11 below.

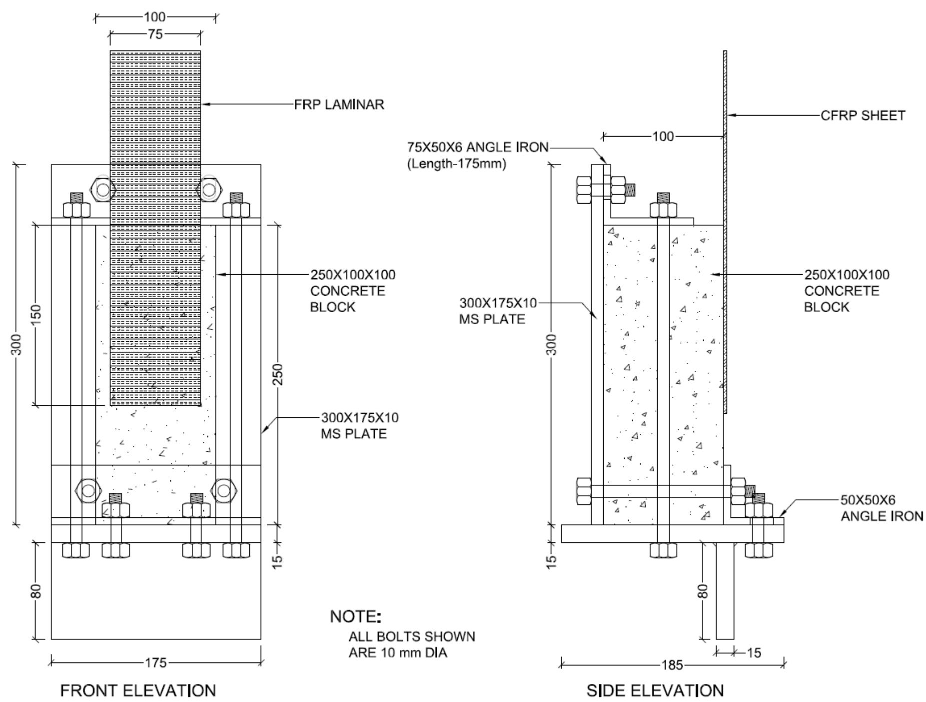

Figure 11. Development of an instrument to maintain the line of load at testing

3.3 Preparation of Test Specimens and testing

To find the effect of moderately elevated temperature curing on bond strength of CFRP/concrete bond for both ambient and elevated temperature conditions, the single shear lap test was selected as the testing arrangement of the research. Similar test methods were used in literature to carry out bond properties in harsh environmental conditions [1, 2, 9, 10, 11 and 16]. Each concrete block, cast using ready mixed concrete and cured, was attached to a strip of CFRP using a commercially available epoxy adhesive. In this chapter, techniques for preparing test specimens, exposing conditions of the samples, and application of loads at testing are discussed.

3.3.1 Surface preparation of concrete blocks

Surface preparation was carried out in the research using the sandblasting method to remove loosely bonded particles on the required face of the concrete block and exposed the much stronger and uniform surface profile for fixing a CFRP layer using epoxy adhesive. This surface preparation methodology is expected to achieve better bonding between CFRP/Concrete specimens. Sandblasting was selected as surface preparation of the concrete specimen in most of past studies carried out to find bond characteristics of FRP/concrete composite [2, 9, and 11]. On top of the prepared concrete surface, a tiny layer of primer application was carried out to enhance the surface energy which facilitates better bonding. Before applying the layer of primer, the prepared surface was brushed to remove dust particles and get a cleaned surface for bonding. The primer layer was cured around 30 minutes, at ambient temperature conditions, ensuring a non-sticky and dry surface in a way to avoid contamination of any other materials like dirt and dust, till it got ready for the application of adhesives on top of the surface.

3.3.2 Assembling of CFRP strip to the test specimen

Application of the adhesive layer was done on top of the primer layer which is applied earlier on the bonding surface of the concrete specimen and then a 225 mm long CFRP sheet was attached by maintaining 150 mm length of the bonding, as shown in Fig. 1. For the purpose of measuring the bond line temperature, it was installed a type K thermocouple with a 1 mm diameter at the center of the bond. Strain gauges were also attached to the CFRP fabric at 35 mm from the laden edge to monitor the strain variation in two mutually perpendicular directions during testing as shown in Fig. 1.

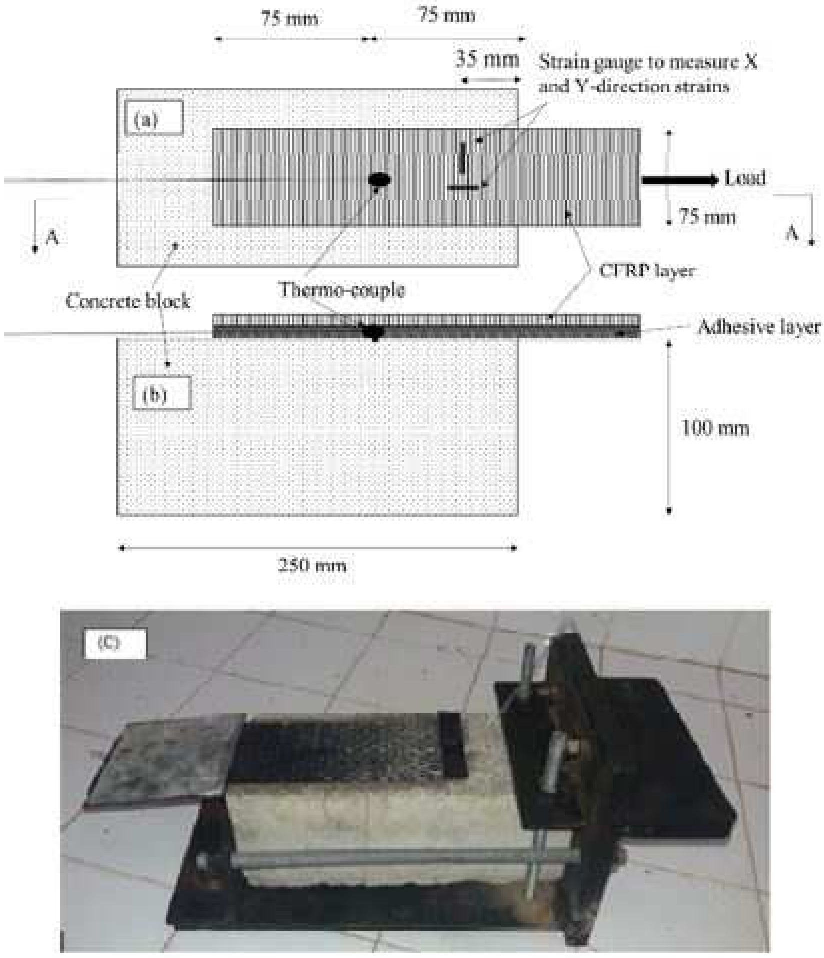

Figure 12. Schematic diagram of a double strap joint; (a) plan view (b) view A-A
(c) prepared sample with instruments

It was finished by attaching two numbers of Aluminum plates to the free end of the CFRP sheet (Fig.1) for the load application at the testing phase. The purpose of this is to ensure a hard well aligned and continuous gripping. Once the preparation process was completed, specimens were cured as described following.

3.3.3 Curing of epoxy adhesive

The objective of this study was set to monitor the effectiveness of curing temperature on the CFRP/Concrete bond line properties. Hence two temperatures were selected as curing conditions of CFRP/concrete bonded specimens. One set of specimens, which was cured at the ambient temperature (30°C) environments. Thirteen samples were cured for the period of one week under this set up. The other set of samples contained twelve numbers of specimens and they were exposed to 75 ± 5 °C elevated temperature initial curing for 4 hours.

Table 2: Configuration of the Curing Process

Specimen group	Initial Curing condition			Total curing time (days)	Total nos. of specimens
	Curing temp (°C)	Method of curing	Initial curing period (hrs.)		
A-1 to A-6	Ambient	Ambient	N/A	14	13
E-1 to E-6	75±5	Floodlights	4	14	12

Instead of using an oven, a 1000 W halogen floodlight system was used to cure the samples in the elevated temperature conditions in this set of studies. Temperature readings on the bond line were monitored using the data logger connected to the thermocouple embedded in the epoxy adhesive interlayer. Then, they were cured at ambient conditions for the remaining period of 7 days before testing. Figure: 13 shows the summary of two curing methods adopted for this test program.

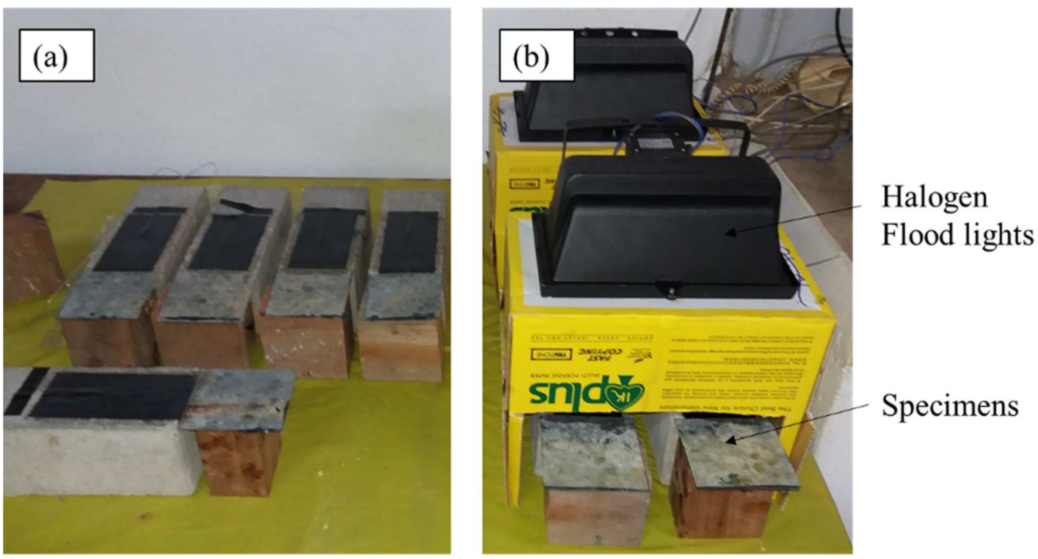

Figure 13. (a) Ambient temperature curing condition (b) Elevated temperature curing

3.4 Testing

The strength test of the prepared specimen was performed using the universal testing machine which has a capacity of 1000 kN. Testing was carried out as a single shear lap test. A transient load was applied directly to prepared samples using the above mentioned testing machine. The test specimen was fixed to the upper clamp of the testing machine using two steel sheets that attached to the CFRP sheet at the preparation of the specimen, and to the lower clamps using steel-plated fixed to the holding instrument of the test specimen as shown in Figure 74.

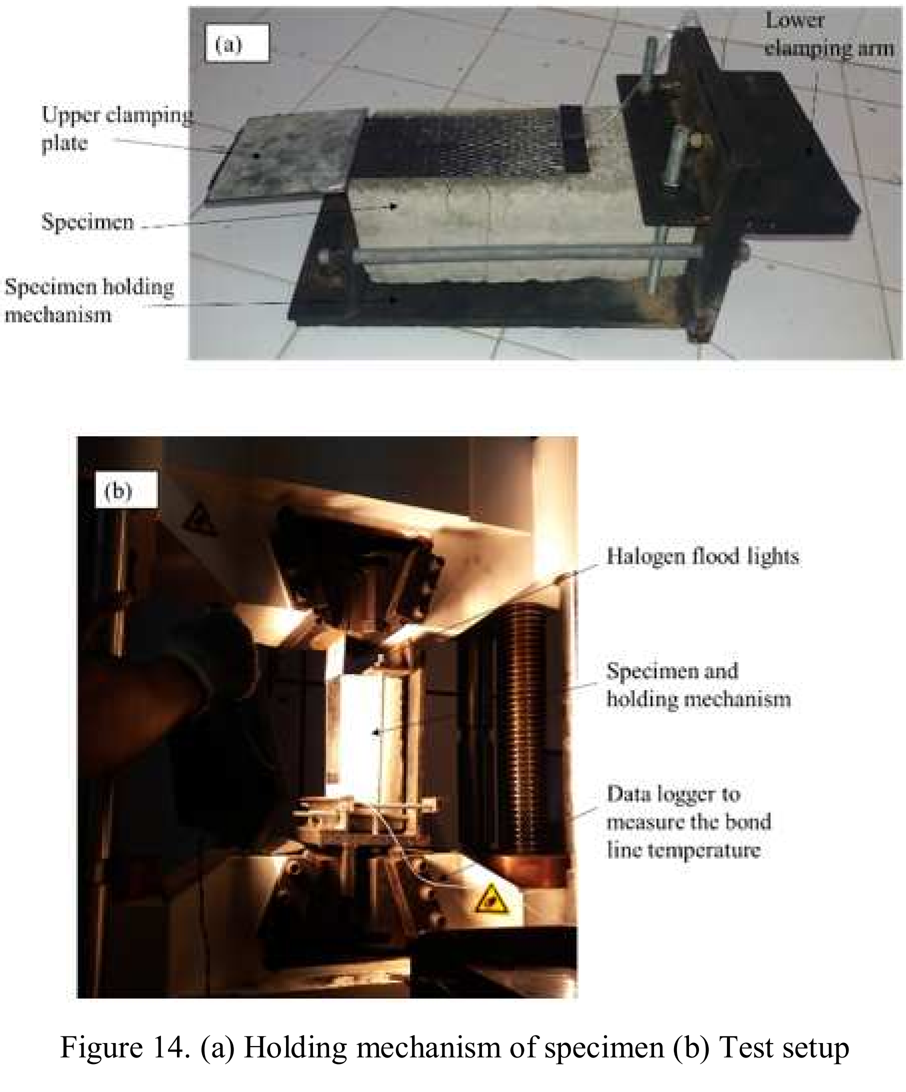

Figure 14. (a) Holding mechanism of specimen (b) Test setup

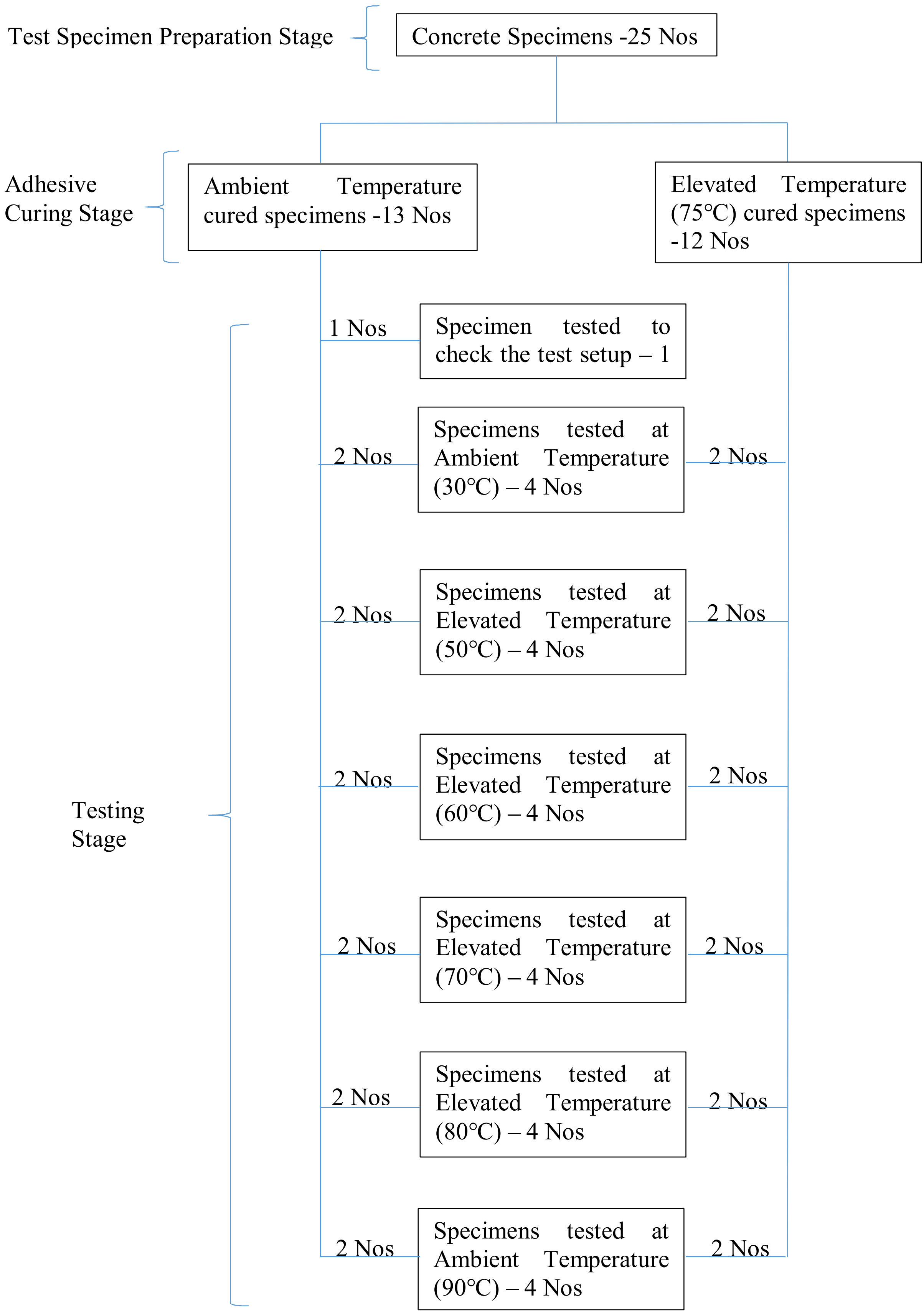

Figure 15. Summarized Specimen Curing and Testing Structures

As per the research objectives, it was decided to investigate the bond performances of the prepared specimens at different temperature levels to determine the level of bond degradation or improvements. A series of Halogen floodlights were used to increase the environmental temperature until the temperature of the bond line reaches the decided constant and stable temperature levels. Elevated temperature levels were selected as ambient temperature (30 °C), 50 °C, 60 °C, 70 °C, 80 °C, and 90 °C and heated the environment before application of transient loading.

3.5 Summary

The experimental procedure is the most important area of this research. All the discussions and conclusions will be based on the results obtained at this phase. Hence it is important to maintain the standard procedures to produce and prepare the specimens as well as for the testing of the specimens. Identification of the properties of the material, which used to produce specimens, is also much more important to justify any deviation of the result, which was obtained in past studies. The selection of sample size and selection of testing methodology was carried out according to the area of studies and the expected outcomes of the research.

In this chapter, it was outlined the material properties used to prepare the test specimens, the important factors considered at the selection of the number of test samples, and other important facts under the preliminary investigations stage and testing procedure including preparation of test specimen.

Under the properties of the material, a detailed description was given about the material used at the casting of concrete prisms as well as the properties of the material used to strengthen the specimens. Further, it elaborated the way of the casting of the concrete prisms including the preparation of moulds to cast concrete prisms. The methodology of curing selected and method of strength verification of the concrete used also were discussed in this section. Under material properties of the polymer based lamination adhesive and, CFRP fiber fabric, which are used for strengthening of concrete prisms, the manufacture delivered properties were presented in this chapter, because of the unavailability of tensile strength testing data of CFRP fiber fabric and unavailability of coupon test data for Lamination Adhesive which used for the study.

The selection of dimensions of the concrete specimens used for the study, the bond length selection for the test, the selection of elevated temperature scheme including duration of heating, which used for curing as well as for testing of the specimen, the selection heating methodology, and the selection of test clamp to fix the specimen for the testing machine, etc., was elaborated under the preliminary investigation.

Further, it discussed the preparation of the test specimen before application of CFRP fiber fabric including surface preparation, application of a layer of primer on the prepared surface, and application of lamination adhesives on it. Introduction of thermocouples to measure the temperature of the layer of lamination adhesive, fixing of CFRP fiber fabric, and the fixing of strain gauges were also elaborated under preparation of the specimen.

Further, it discussed the step-by-step procedure carried out under the curing stage for both specimens subjected to elevated temperature curing as well as the curing at ambient temperature conditions.

04. Effects of curing condition on bond performance

4.1 Introduction

Data analysis of research is the most important component of the research. It needs to be carried out in a way to achieve the main objective of the research. Identification of the effects of elevated temperature curing on the glass transition temperature of CFRP/concrete bond was the main objective of this research and the result from the analysis was carried out towards achieving this objective. Test data of the ultimate strength analysis tested for each temperature level are represented in this chapter. Further analysis of test results will be carried out here. Extracting the relationship between test results with curing temperature and testing at elevated temperature further discussed here.

4.2 Test Results

One of the specimens out of 25 has been used to set test setup to the universal testing machine and to see how it works and what the limitations and errors could occur during the testing methodology. This was conducted as a guide to carry out the additional adjustment to the test setup and finally, the failure loads of 24 specimens are used for the analysis of the results as carried out below. While carrying out the test, due to failure of tread bar in the test set up one of the test results had to be ignored from the data analysis.

4.2.1 Failure loads Vs. Testing Temperatures

According to the test data, it was noticed that there are some differences in failure load values of the specimen although their curing conditions and testing temperatures are equal. This kind of variation may happen due to non-homogeneous characteristics of concrete specimens even though they were cast in the same grade concrete. In addition to that, some of the human errors may happen at the specimen preparation as well as at the testing stage. Hence it was decided to use the average values of test results for analysis.

4.2.1.1 Failure loads of the specimens cured under ambient temperature conditions

The ultimate strength test data for the specimens which cured under ambient temperature for each temperature level and average failure loads are represented in Table 3 given below.

Table 3. Measured failure loads for the specimen cured at ambient temperature

Testing temperature (^{0}C)	Ambient temperature cured specimen			
	Specimen identification	Failure load (kN)		Average Failure load (kN)
30	A-1	14.7	11.95	13.325
50	A-2	8.75	11.15	9.95
60	A-3	9.85	8.1	8.975
70	A-4	7.45	6	6.725
80	A-5	8.85	5.35	7.1
90	A-6	9.4	3.25	6.325

The Graphical representation of the failure loads vs. tested temperature for the specimen cured under ambient temperature shown in Figure 16.

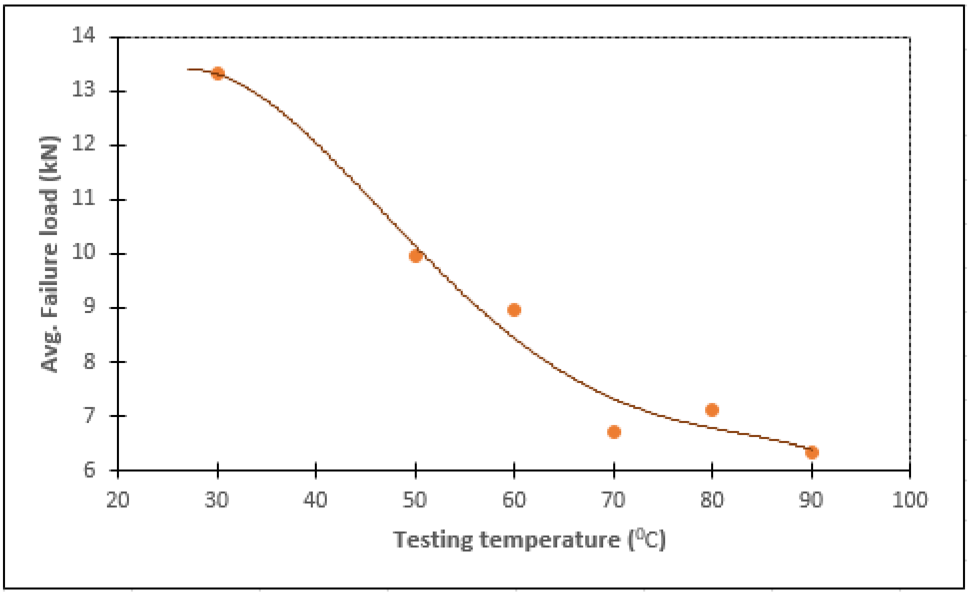

Figure 16. Average Failure load Vs. Testing temperature for the samples, which cured under ambient temperature

According to the test data of the failure loads of the specimens cured at ambient temperature showed a significant reduction with the increment of the testing temperature. This behavior of the curve is very much similar to the curve shown in Figure 01, which is extracted from Gamage [9]. The curve obtained from the literature, presented the residual strength variation of the CFRP/ Concrete joint of samples which cured under ambient temperature conditions, which tested at various temperatures. The linear portion of the curve indicates the higher rate of strength reduction with the increase of the temperature.

4.2.1.2 Failure loads for elevated temperature cured specimens

The ultimate strength test data for the elevated temperature cured specimens for each temperature level and average failure loads are represented in Table 4 given below.

Table 4. Measured failure loads for the specimen cured at Elevated temperature

Testing temperature (^{0}C)	Elevated temperature cured specimen			
	Specimen identification	Failure load (kN)		Average Failure load (kN)
30	E-1	16.25	14.15	15.20
50	E-2	15.90	12.80	14.35
60	E-3	12.50	11.40	11.95
70	E-4	11.80	9.90	10.85
80	E-5	13.35	7.75	10.55
90	E-6	10.95	6.75	8.83

The Graphical representation of the failure loads vs. tested temperature for the specimen cured under elevated temperature shown in Figure 17.

The curve for elevated temperature cured samples also showed similar behaviour as ambient temperature cured specimens as well as the curve extracted from the literature.

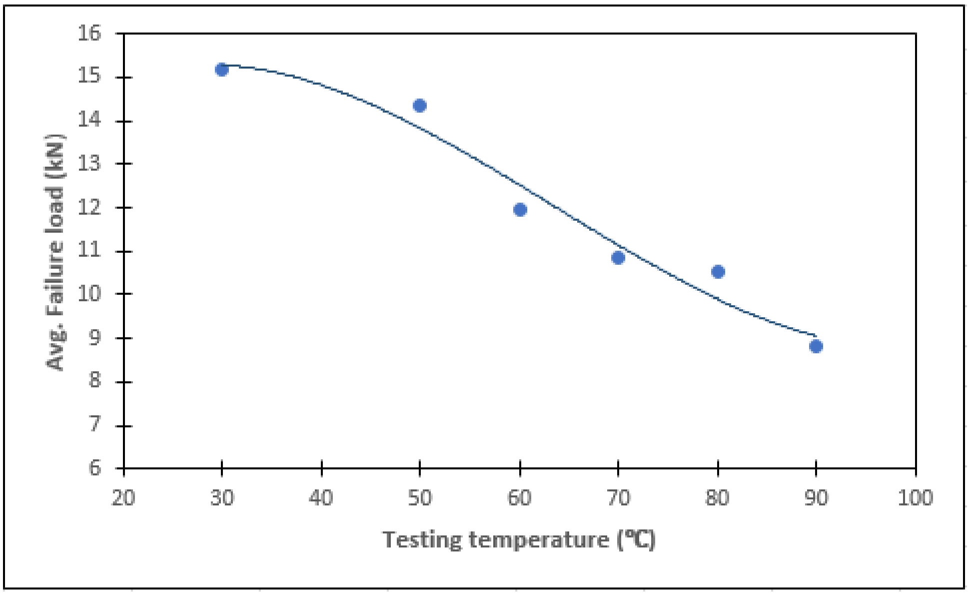

Figure 17. Average Failure load Vs. Testing temperature for the specimens cured at elevated temperature

Elevated temperature cured samples also showed strength reduction with temperature. The comparison of the results which recorded for the samples, cured under ambient temperature conditions, with the results recorded for the samples which cured at elevated temperature conditions showed the higher strength for the same temperature levels. The steeper curve showed the graphical representation of the results of elevated temperature cured specimens.

Table 5. Average failure loads for both specimens cured under ambient temperature conditions & elevated temperature conditions

Testing temperature (^{0}C)	Specimens cured at Ambient temperature conditions		Specimens cured at Elevated temperature conditions	
	Specimen	Failure load (Avg) (kN)	Specimen	Failure load (Avg) (kN)
30	A-1	13.32	E-1	15.20
50	A-2	9.95	E-2	14.35
60	A-3	8.98	E-3	11.95
70	A-4	6.72	E-4	10.85
80	A-5	7.10	E-5	10.55
90	A-6	6.32	E-6	8.82

The Graphical representation of the failure loads vs. tested temperature for the specimen for both cured under ambient temperature and cured under elevated temperature showed separately in Figure 18.

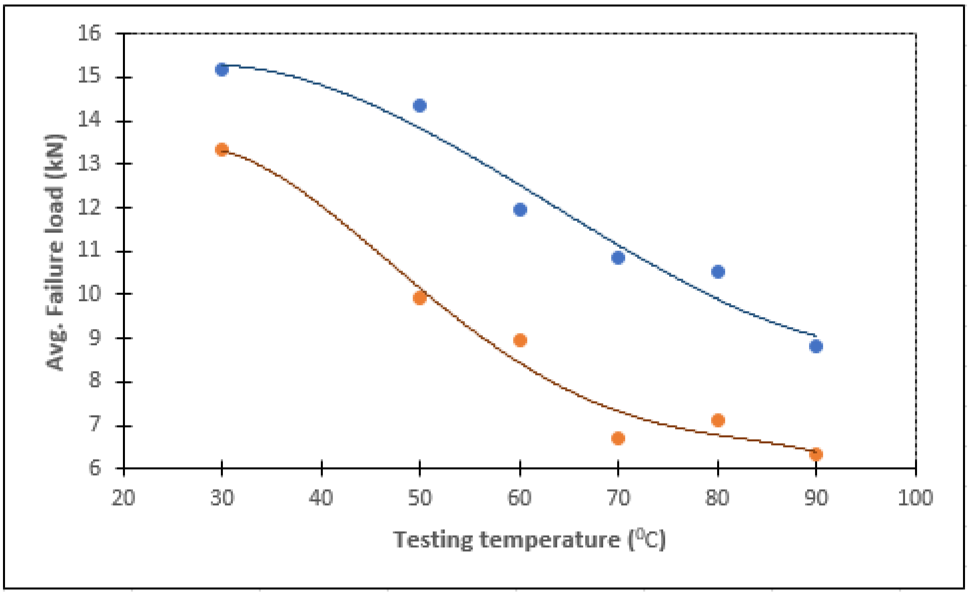

Figure 18. Average Failure load Vs. Testing temperature information of the specimens cured under both ambient and elevated temperature conditions

When analyzing both the curves simultaneously, a considerable strength gaining was recorded for the elevated temperature cured samples that were tested. Similar observations recorded by Edward [7] with his studies carried out to find the properties of epoxy alone. According to Edward, the epoxy systems cured at elevated temperatures rearrange with higher cross-linking density. The researcher further argued that the glass transition point of the elevated temperature cured samples are higher than the polymers that are formulated for room temperature curing. Further, he mentioned that the elevated temperature curing epoxies showed much better shear strength, and better environmental resistance than ambient temperature cured specimens as advantages, and as disadvantages, these specimens are poor in toughness and peel strength.

Strength achievement at each temperature level is also important when considering the practical aspects of elevated temperature curing. Strength achievement at each temperature level and percentage strength achievement for each temperature was tabulated below in Table 6.

Table 6. Strength achievement and pecentage of strength achievement for both ambient temperature cured & elevated temperature cured specimen

Testing temperature (^{0}C)	Average Failure load for ambient temperature cured specimens (kN)	Average Failure load for elevated temperature cured specimens (kN)	Strength achievement (kN)	Percentage Strength achievement (%)
30	15.2	13.325	1.875	14.07
50	14.35	9.95	4.4	44.22
60	11.95	8.975	2.975	33.15
70	10.85	6.725	4.125	61.34
80	10.55	7.1	3.45	48.59
90	8.825	6.325	2.5	39.53

The strength achieved due to elevated temperature curing in each temperature was plotted in Figure 19 below.

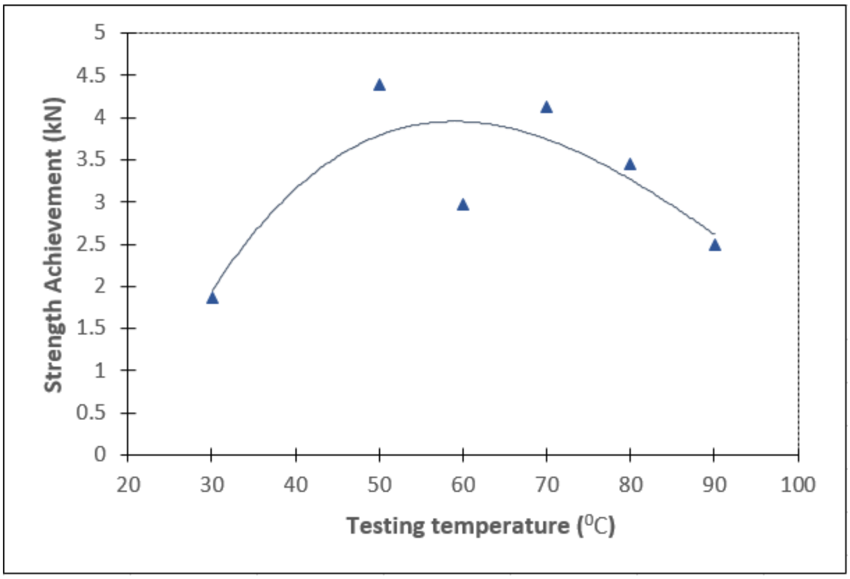

Figure 19. Strength achievement of specimens due to elevated temperature curing in each temperature

According to this graphical representation, the highest strength achieved was slightly around 3.8kN at the temperature of 58°C.

Similarly, the graphical representation of percentage strength achievement due to elevated temperature curing in each temperature was shown in Figure 20.

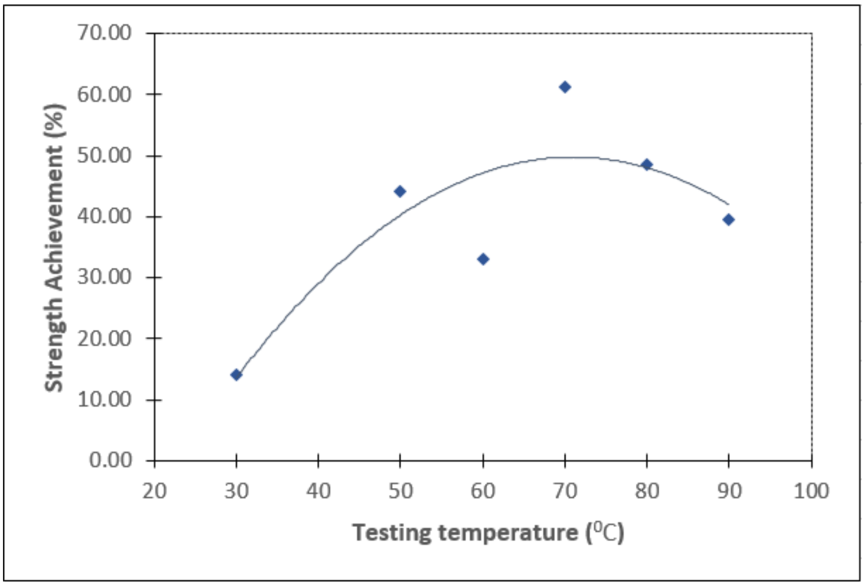

Figure 20. Percentage strength achievement of specimens due to elevated temperature curing in each temperature

Elevated temperature cured concrete/epoxy/CFRP samples have shown higher strength compared to ambient temperature cured concrete/epoxy/CFRP samples. However, at the room temperature (30 ^{0}C), the strength of the bond of elevated temperature cured and the ambient temperature cured specimens had less variation with a difference of 14% between average failure loads. At bond line temperatures more than 50 ^{0}C, the average increase in bond strength of elevated temperature cured CFRP /concrete bond is 40%, compared with the ambient temperature cured bond. The highest difference between elevated temperature cured and ambient temperature cured bond strengths were observed at 70 ^{0}C bond line temperatures with a 48% difference.

By considering both the graphs, it can be understood that there is no relationship between the highest strength achievement with the highest percentage strength achievement due to elevated temperature curing. But this information may be used in construction engineering, to enhance strength properties of the CFRP/Concrete bonded surfaces.

4.2.2 The glass transition temperature (T_g) of the polymeric bond

Behavior of Glass transition temperature for two different curing conditions on concrete/epoxy/CFRP single shear lap joints are shown in Fig. 19. Gamage et. al. [9] and Chandrathilaka et. al [6] used the nominalized percentage load and bond line temperature to define the glass transition temperature of the polymer adhesive which is used in CFRP/epoxy/concrete bond. The normalized percentages were obtaned by dividing the ultimate load of a sample by the average ultimate load of ambient temperature cured specimens which tested at ambient temperature. Intersection of tangents method was used here to obtain the Tg of epoxy adhesive similar to literature [6, 9].

Glass transition temperature, T_g of CFRP/epoxy/concrete bond is found as 46 ^{0}C for ambient temperature cured samples, while the T_g of pure epoxy adhesive [21] is 65 ^{0}C. A 30% reduction in T_g has been observed in the polymer layer, which is used in CFRP/epoxy/concrete bond line and the pure epoxy adhesive. The same pattern has been observed by Chandrathilaka et. al. [6] for the steel/epoxy/CFRP bond and pure epoxy adhesive. This indicates the significance of measuring the Glass transition temperature, T_g of the adhesives, which is used for CFRP/concrete bonding, without relying on the manufacturer specified glass transition temperature, T_g for pure epoxy adhesive.

Glass transition temperature, T_g of the concrete/epoxy/CFRP bond Tg has been increased by 11% for elevated temperature cured specimens, when compared to the ambient temperature cured samples. However, Chandrathilaka et al. [6] experienced a 20% increment in T_g for the CFRP/epoxy/steel bond with elevated temperature curing compared to ambient temperature cured bond. The low thermal conductivity and high specific heat of concrete compared to steel [10, 13] may cause concrete to take more time to increase the bond line temperature to 75 ^{0}C than steel/epoxy/CFRP bond. This may lead to a decrease in performance of elevated temperature curing in concrete/epoxy/CFRP bond compared to steel/epoxy/CFRP bond. The enhancement of the glass transition temperature, T_g, of the bond improves the ability to withstand against humidity of the environment, to the long term exposures to the cyclic temperature, and sustained loading conditions [5, 17] showed that increase T_g value of

CFRP/epoxy bonds leads to effective and economical application with insulation to resist during fire exposures. Therefore, the curing at elevated temperature of the CFRP/epoxy/concrete has higher importance considering the fire performance and service performance.

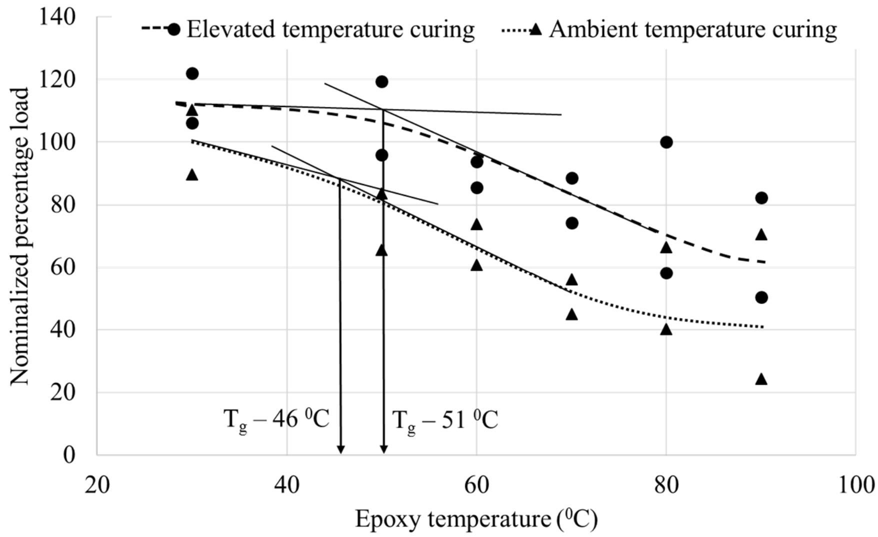

Figure 21. Glass transition temperature for two curing conditions

4.2.3 Variation of mechanical properties of bond with elevated temperature

Variation of mechanical properties of the adhesive layer of the CFRP/Concrete bond was extracted for both ambient temperature cured specimens and elevated temperature cured specimens. This was carried out assuming the adhesive properties given in Table 1 as properties of adhesive at ambient temperature for ambient temperature cured specimens. It was multiplied by normalized load factor and got the values for the different curing conditions and testing temperatures.

Figure. 22 shows the variation of mechanical properties of the adhesive layer of bond with elevated temperature. To extract variations of mechanical properties of the adhesive layer of bond with elevated temperature for both ambient temperature cured specimens and elevated temperature cured specimens, CFRP/epoxy/concrete joint strength reduction extracted from the experimental program was considered the differences in properties of the adhesives against the temperature.

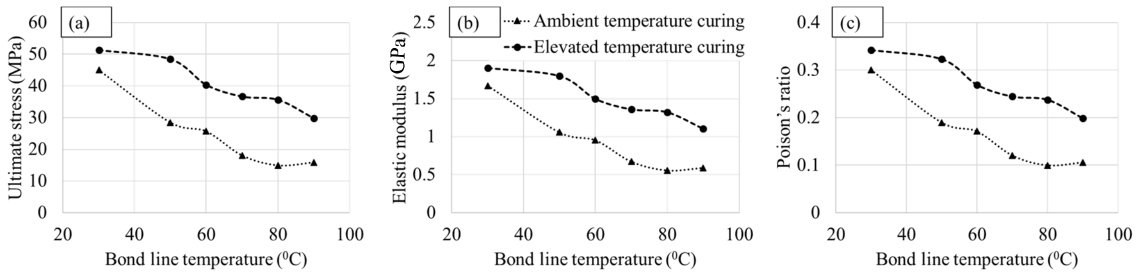

Figure 22. Variation of mechanical properties of the CFRP/epoxy/concrete bond (a) Ultimate stress (b) Elastic modulus (c) Poisson's ratio

All three adhesive properties, (a) Poisson's ratio (b) Elastic modulus and (c) Ultimate stress, have shown a reduction with temperature increment in the bond line. It was assumed that, the Material property variations of the concrete and the CFRP is considered as negligible when compared with the variation of adhesive bond properties at a temperature less than 90 ^{0}C.

4.2.4 Failure modes

The failure patterns observed for the lesser testing temperature than 50°C, for ambient temperature cured specimens were a mixture of concrete fracture failure to concrete rupture failure. Similar observations were found in the literature for the specimens tested below 50°C, which cured at ambient temperature [9 & 11]. The properties of concrete can be considered as the critical factors for this bond failure.

For the testing temperature of 50°C, elevated cured samples showed concrete fracture failure while ambient cured samples showed a cohesive failure. These failure modes are presented in Figure 23 below.

The figure 23, exhibits evidence for better bonding characteristics in elevated temperature cured specimens at 50°C. At this testing temperature, failure mode transferred from pure bonding failure of the adhesive layer to mixture of concrete rupture failure and bonding failure towards the concrete surface as a result of strength improvement achieved on CFRP/concrete specimen, due to elevated temperature curing. This strength achievement indicates the improvement of characteristics of the adhesive layer. Further, this indicated that the T_g value given in the manufacture's specification is not correct. Hence for designing purposes, it is advisable to carry out a coupon test for every adhesive, which is going to be used, to identify the actual T_g of the adhesive.

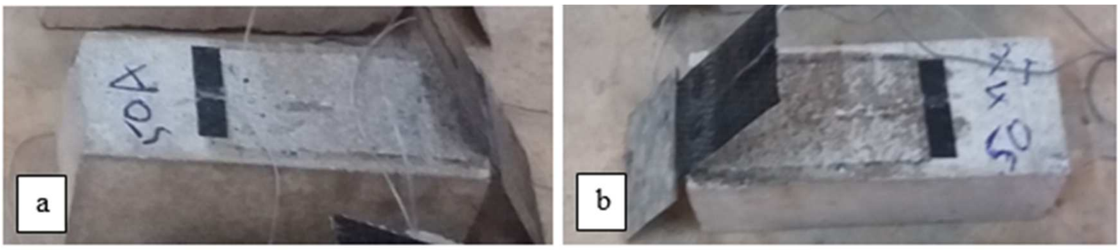

Figure 23. Failure modes at 50°C; a) Ambient temperature cured specimen, b) Elevated temperature cured specimen.

As described in the literature, this may be due to better cross-linking occurring at elevated temperature curing. This can be further explained using the molecular mobility of adhesive. Due to exposure to an elevated temperature at the curing stage, increase in mobility of the molecules of the adhesive. As a result of this, the toughness of the adhesive layer increased, and a reduction of cohesive characteristics.

For the testing temperature of 60°C, both elevated cured samples and ambient cured samples showed a cohesive failure. These failure modes are presented in Figure 24 below.

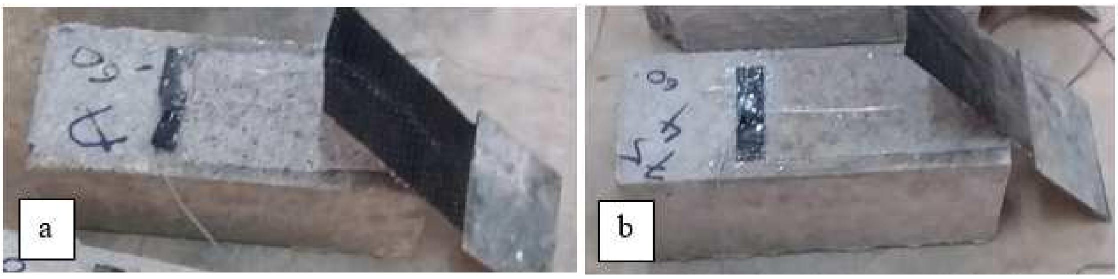

Figure 24. Failure modes at 60°C; a) Ambient temperature cured specimen, b) Elevated temperature cured specimen.

According to the above failure modes, for 60°C testing temperature, cohesive failure of adhesive was shown for both elevated cured specimens as well as ambient cured specimens. According to the analyzed results, the improved T_g for elevated temperature cured specimens were 51°C. Hence this observation emphasizes the improvement of Tg in elevated temperature curing.

This indicates that improving the glass transition temperature is one of the better solutions for retaining strength on CFRP/Concrete bonds at higher temperature environments. Generally, the adhesive tends to fail in higher temperatures than its improved Glass Transition Temperature, by elevated temperature curing.

In this research study, as elevated temperature curing, the specimens were subjected to 75°C for 4hrs at the initial curing period only. The specimens were kept under ambient temperature for the balance curing period. The testing was performed at different temperatures and got the above results and justifications. In the future, as an improvement area, the strengthened specimens must be subjected to different curing temperatures for different curing periods to find suitable curing temperatures for the curing period to achieve maximum glass transition temperature. Further, should identify the maximum temperature that can withstand the concrete without affecting its strength, which can be affected by CFRP/Concrete bond.

4.2.5 The behavior of Stress vs. Slip

The universal testing machine itself recorded several effects related to the stress applied. This can be considered as more accurate readings when comparing with the other method of monitoring with human involvement.

One such monitored data was a variation of stresses and the relative displacement on the jaws of the testing equipment (universal testing machine). The use of testing apparatus minimizes the relative slipping between the specimen and the jaws of the testing machines. Hence it was assumed here that the recorded displacement is equal to the slipping that exists at the CFRP/Concrete joint. The following curves showed the behaviour of the slipping recorded against the stresses applied.

For ambient temperature cured samples, the Stress vs. Slip variation is shown in Figure 25 while the same for elevated temperature cured specimens are shown in Figure 26.

At a glance, the higher stress and the higher slip was monitored in elevated temperature cured samples.

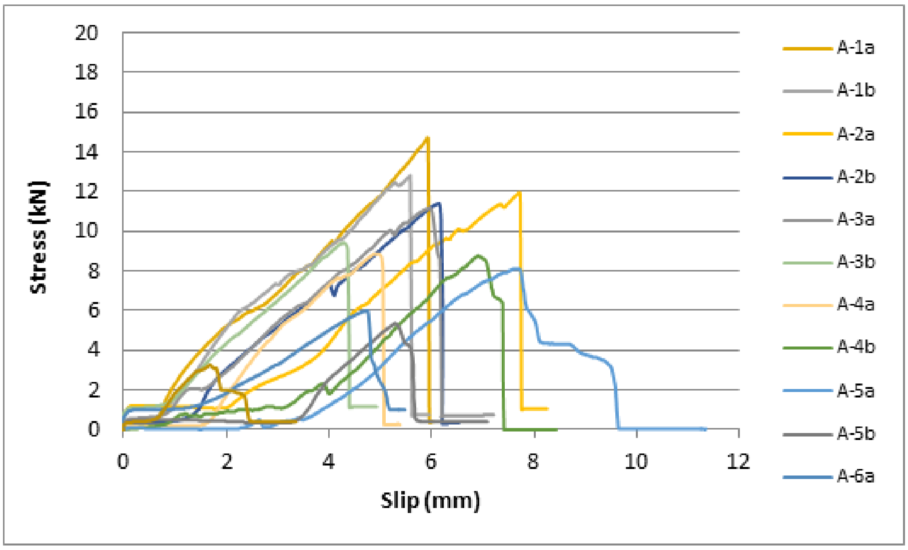

Figure 25. Stress vs. Slip Curve for Ambient temperature cured specimens

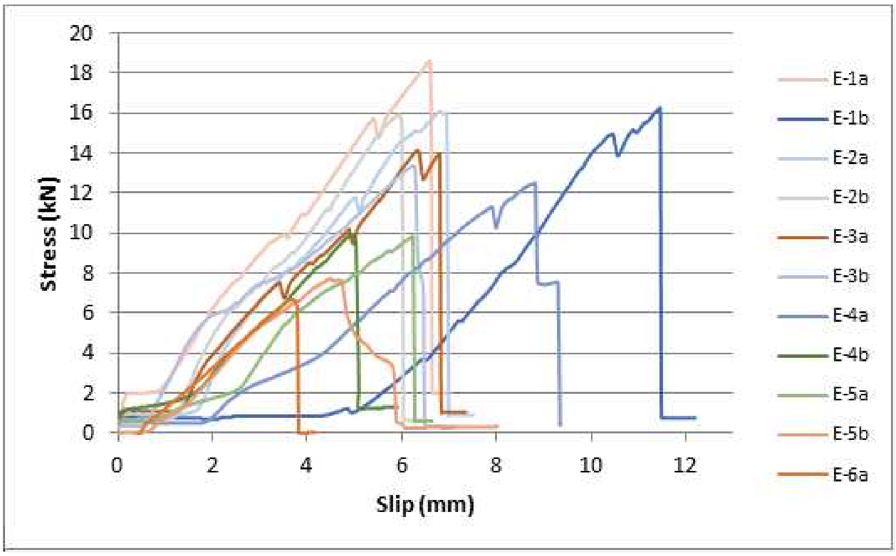

Figure 26. Stress vs. Slip Curve for Elevated temperature cured specimens

In the Stress-Slip response, some of the kinks are visible near the peak of applied stresses for some of the samples. According to the literature, there may be a relationship of kinks to macro cracks which appeared in the concrete, on near-surface to the epoxy layer [7].

For further analysis of stress vs. slip, curves are separated according to the tested temperatures, which exhibit much more clear behaviour.

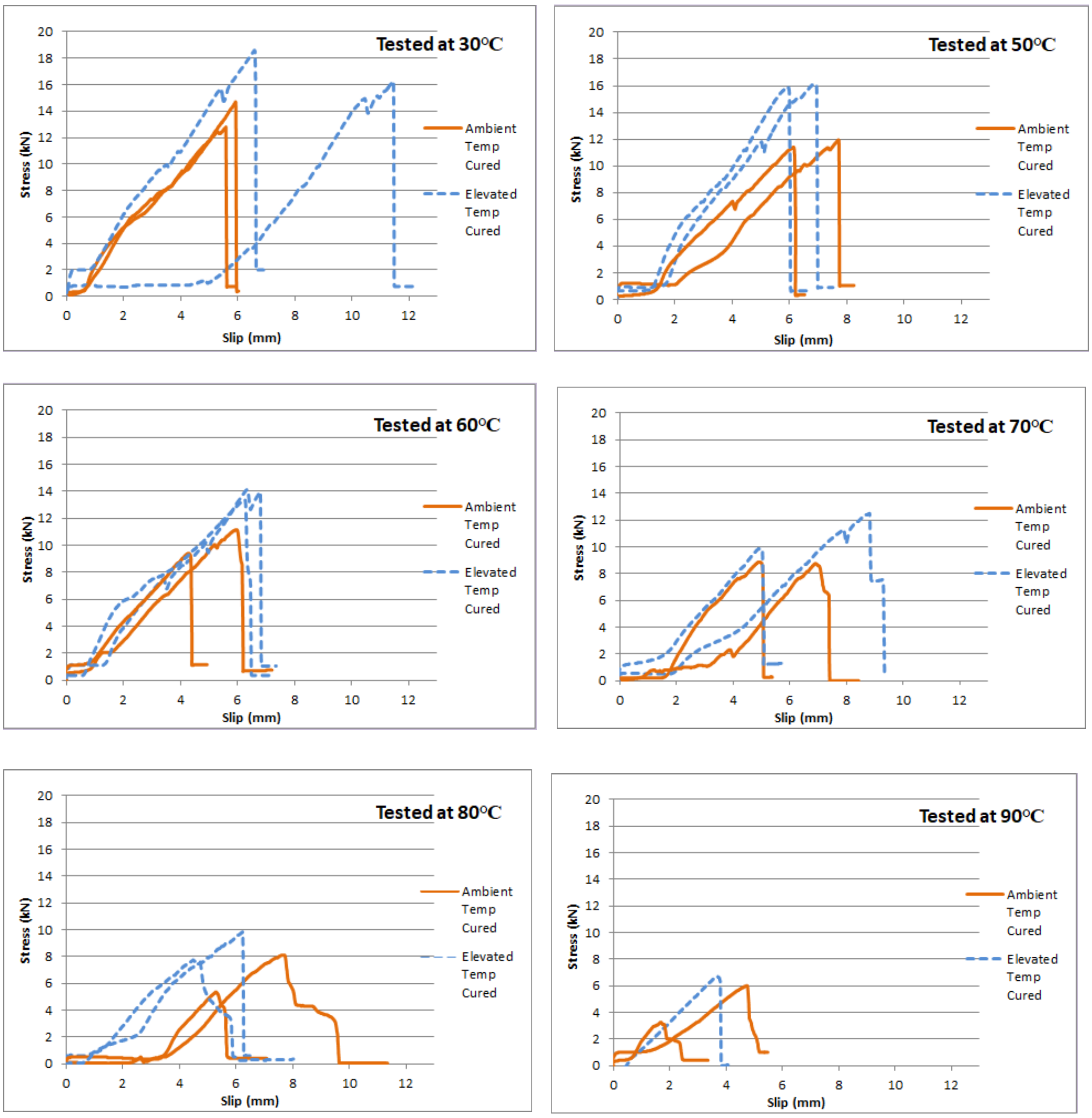

Figure 27. Stress vs. Slip Curve according to tested temperature for both Ambient and Elevated temperature cured specimens

When considering above the stress vs. slip curves, with the gradual increment of tested temperature increases, the stress withstanding stresses decline gradually. At the lower testing temperatures, the elevated temperature cured samples showed much higher stress and slip compared to ambient temperature cured samples.

When the tested temperature increased stress was low and the higher slip was recorded within short periods. Further, it was noticed that the kinks were not recorded in the load slip curves, indicating that cohesive failure has occurred at these higher testing temperatures.

4.2.6 Strain Variations

At the preparation of specimens, the strain gauges were attached to the selected samples. This sample selection was done in a way to select all the testing temperatures as well as both curing conditions. Due to the wrong selection of data logger, strain gauge data, for lower testing temperatures, are not available.

Two strain gauges were attached to each of the selected samples, in two directions, parallel to load and perpendicular to load, which represented X and Y directions respectively. Recorded reading in the strain gauge at X-direction was plotted in Figure 28, shown below.

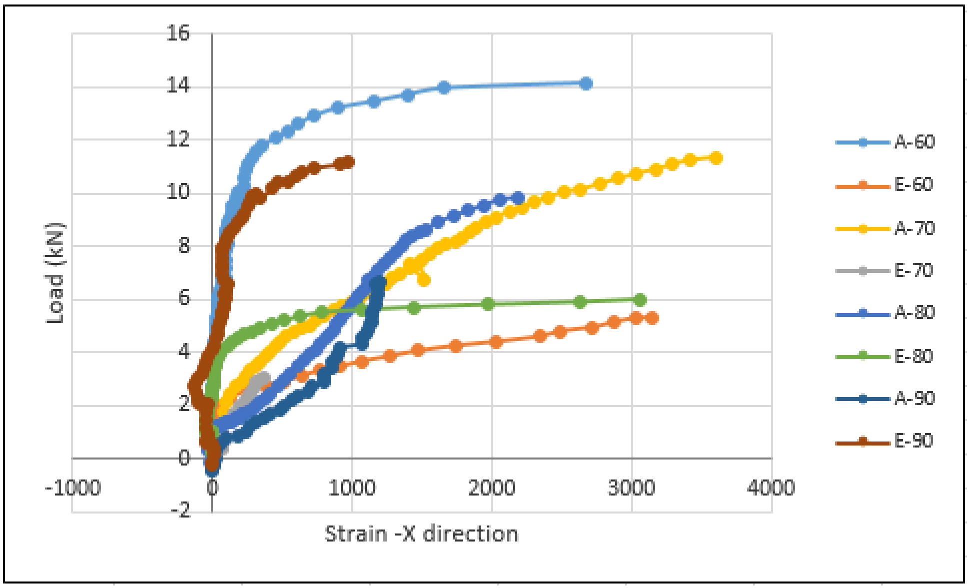

Figure 28: Load vs. Strain Variation – X direction for both Ambient and Elevated temperature cured specimens

Recorded reading in the strain gauge at Y-direction was plotted in Figure 29, shown below.

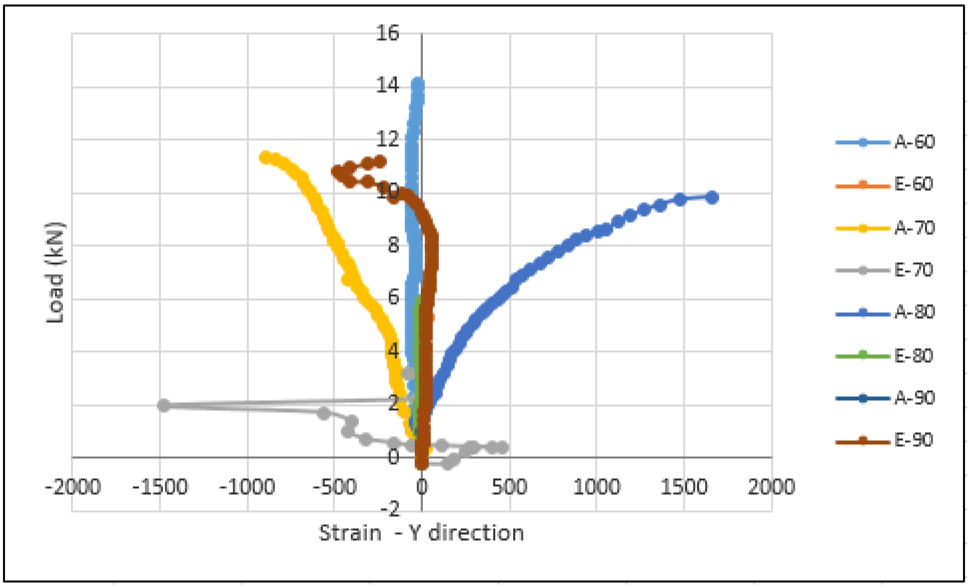

Figure 29: Load vs. Strain Variation – Y direction for both Ambient and Elevated temperature cured specimens

When considering graphs given above, any direct relationship can be identified in strain variation with neither ambient nor elevated temperature cured specimens.

05. Conclusions and Recommendations

Concluding the research findings undertaken in this chapter. Under the conclusion, it needs to forward all the findings in this work of the study and needed to show the relationship with other related findings identified in the literature.

The main objective of the research was identified as finding the effects on the glass transition temperature of CFRP/concrete bonds when they are exposed to elevated temperature curing. To undertake these objectives, the testing approach was streamline with exploration of the bond performances of the CFRP/concrete specimens which cured at different temperature levels against the ambient temperature cured specimens. To accomplish this, twenty-five concrete blocks were made using grade 30 ready mixed concrete and cured for 28 days. The preparation of the surfaces of the concrete specimens were performed using sandblasting technique. A commercially available type of epoxy adhesive was used to attach 75 mm wide CFRP strips to each of the concrete prisms. Halogen floodlights were used in the study to set the curing temperature. The selected elevated temperature levels were ambient temperature (30 °C), 50 °C, 60 °C, 70 °C, 80 °C, and 90 °C at the period of testing, the environment was heated before application of transient loading. Testing of the CFRP/concrete was carried out as a single shear lap test. Load application was performed with the help of a universal testing machine having 1000 kN capacity. Based on the outcomes of the research study, the conclusions were defined.

The specimens which cured at ambient temperature exhibited a major reduction in forces at the failure, with the increment of the testing temperature. The linear portion of the failure loads vs. temperature curve indicates that the higher rate of strength reduction and it was greater near the T_g. Hence T_g lies in this linear portion of the curve of the used polymer. This drastic strength declining behavior of polymer adhesive against increasing temperature near T_g was also identified in the literature.

According to the results received for ambient temperature cured samples, T_g of the used polymer adhesive to bonding of CFRP/concrete joint, for the studies was identified as around 46°C. This value is much lower than the mentioned value of T_g in the manufacture's specification.

With the enhancement of testing temperature, the elevated temperature cured specimens also showed the drastic declining behaviour in failure load. According to the temperature vs. normalized percentage load graph, T_g of polymer adhesive is extracted. The enhanced T_g of the used polymer for elevated temperature cured specimens is recorded as 51°C.

Considerable strength gaining was identified for the elevated temperature cured specimens at the testing temperature range of 60°C to 80°C. When increasing the testing temperature, strength gaining of the CFRP/Concrete bond due to elevated temperature curing was reduced.

Enhancement of T_g due to elevated temperature curing is recorded from 46°C to 51°C and it is 11% increment of T_g than ambient temperature cured specimens.

Strength achievement is around 3.8kN at the testing temperature of 60°C.

The percentage strength achievement due to elevated temperature curing is 48% than the specimens cured at ambient temperature for the testing temperature range of 70°C.

The failure mode of the specimens varied with testing temperature and for lesser temperature levels than 50°C, it was the mixture of concrete fracture failure to concrete rupture failure for both elevated temperatures cured specimens and ambient temperature cured specimens depending on the properties of concrete. At 50°C, the failure mode of the testing temperature of elevated cured samples was concrete fracture failure and that of ambient temperature cured samples was a cohesive failure. At the testing temperature of 60°C, the failure mode of both elevated cured samples and ambient temperature cured samples were a cohesive failure. At the observations of failure patterns, there is a strong improvement in elevated cured specimens at the testing temperature of around 50°C. When it considered a lesser the testing temperature, than the value of Tg of the polymer adhesive it showed a mixture of concrete fracture failure to concrete rupture failure while in higher the testing temperature than the value of Tg of the adhesive, it showed cohesive failure. Hence, it was clear that this failure mode has a relationship with Tg.

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07. Annexes

List of Annexes

Nominalized percentage load calculation

Specimen identification	Testing temperature (^{0}C)	Failure load (kN)	Normalized percentage load
A-1 (a)	30	14.70	110.32
A-2 (a)	50	8.75	65.67
A-3 (a)	60	9.85	73.92
A-4 (a)	70	7.45	55.91
A-5 (a)	80	8.85	66.42
A-6 (a)	90	9.40	70.54
A-1 (b)	30	11.95	89.68
A-2 (b)	50	11.15	83.68
A-3 (b)	60	8.10	60.79
A-4 (b)	70	6.00	45.03
A-5 (b)	80	5.35	40.15
A-6 (b)	90	3.25	24.39
E-1 (a)	30	16.25	121.95
E-2 (a)	50	15.90	119.32
E-3 (a)	60	12.50	93.81
E-4 (a)	70	11.80	88.56
E-5 (a)	80	13.35	100.19
E-6 (a)	90	10.95	82.18
E-1 (b)	30	14.15	106.19
E-2 (b)	50	12.80	96.06
E-3 (b)	60	11.40	85.55
E-4 (b)	70	9.90	74.30
E-5 (b)	80	7.75	58.16
E-6 (b)	90	6.75	50.66

Variation of mechanical properties of the CFRP/epoxy/concrete bond

Specimen Identification	Testing Temperature (^0C)	Average Failure load (kN)	Ultimate Stress (MPa)	Elastic Modulus (GPa)	Poison's Ratio
A-1	30	13.32	45.00	1.67	0.3
A-2	50	9.95	33.61	1.25	0.22
A-3	60	8.98	30.34	1.13	0.20
A-4	70	6.72	22.70	0.84	0.15
A-5	80	7.1	23.99	0.89	0.16
A-6	90	6.32	21.35	0.79	0.14
E-1	30	15.2	51.35	1.91	0.34
E-2	50	14.35	48.48	1.80	0.32
E-3	60	11.95	40.37	1.50	0.27
E-4	70	10.85	36.66	1.36	0.24
E-5	80	10.55	35.64	1.32	0.24
E-6	90	8.83	29.83	1.11	0.20

Load vs Strain Analysis

Specimen	Strian Gauge Value		Load	Calculated Variation	
A-60	Recorded X	Recorded Y	Recorded	X	Y
1	-111	-70	0	0	0
2	-106	-69	0.25	5	1
3	-116	-85	0.8	-5	-15
4	-123	-95	1.1	-12	-25
5	-126	-98	1.15	-15	-28
6	-126	-99	1.1	-15	-29
7	-128	-99	1.15	-17	-29
8	-131	-101	1.1	-20	-31
9	-135	-103	1.1	-24	-33
10	-141	-110	1.1	-30	-40
11	-144	-116	1.1	-33	-46
12	-146	-121	1.1	-35	-51
13	-145	-125	1.1	-34	-55
14	-141	-119	1.1	-30	-49
15	-139	-116	1.1	-28	-46
16	-137	-115	1.05	-26	-45
17	-138	-115	1.1	-27	-45
18	-137	-114	1.2	-26	-44
19	-131	-112	1.4	-20	-42
20	-130	-112	1.85	-19	-42
21	-128	-114	2.3	-17	-44
22	-122	-115	2.75	-11	-45
23	-114	-116	3.1	-3	-46
24	-108	-118	3.4	3	-48
25	-103	-121	3.7	8	-51
26	-100	-123	3.9	11	-53
27	-98	-124	4.15	13	-54
28	-96	-125	4.35	15	-55
29	-92	-125	4.6	19	-55
30	-88	-127	4.85	23	-57
31	-85	-128	5.1	26	-58
32	-83	-129	5.3	28	-59
33	-79	-129	5.55	32	-59
34	-76	-128	5.75	35	-58
35	-72	-129	5.95	39	-59
36	-68	-131	6.15	43	-61
37	-57	-130	6.35	54	-60
38	-49	-127	6.6	62	-57
39	-38	-116	6.8	73	-46
40	-31	-110	7	80	-40
41	-25	-107	7.2	86	-37
42	-23	-107	7.4	88	-37
43	-20	-108	7.5	91	-38
44	-16	-107	6.8	95	-37
45	-12	-107	7.15	99	-37
46	-23	-106	7.6	88	-36
47	-16	-109	7.85	95	-39
48	-8	-104	8.05	103	-34
49	-9	-112	8.2	102	-42
50	-12	-118	8.4	99	-48
51	-13	-119	8.5	98	-49
52	-9	-123	8.6	102	-53
53	-8	-124	8.8	103	-54
54	-3	-128	8.9	108	-58
55	11	-127	9.1	122	-57
56	21	-128	9.3	132	-58
57	28	-129	9.5	139	-59
58	40	-131	9.5	151	-61
59	54	-132	9.85	165	-62
60	70	-132	10.05	181	-62
61	85	-131	9.85	196	-61
62	98	-131	9.7	209	-61
63	112	-132	10.3	223	-62
64	108	-131	10.6	219	-61
65	128	-133	10.85	239	-63
66	146	-133	11.1	257	-63
67	172	-132	11.3	283	-62
68	204	-131	11.55	315	-61
69	249	-128	11.8	360	-58
70	346	-123	12.05	457	-53
71	431	-120	12.3	542	-50
72	506	-114	12.6	617	-44
73	614	-108	12.9	725	-38
74	783	-103	13.2	894	-33
75	1040	-99	13.45	1151	-29
76	1282	-98	13.7	1393	-28
77	1543	-99	13.95	1654	-29
78	2563	-93	14.15	2674	-23
79	3366	-99			
80	3921	16			
81	4287	774			
82	4377	1011			
83	4529	1120			
84	4636	1267		4747	1337
85	4717	1336		4828	1406
86	4744	1416		4855	1486
87	785	2571		896	2641
88	771	2376		882	2446
89	771	2218		882	2288

Specimen	Strian Gauge Value		Load	Calculated Variation	
E-60	Recorded X	Recorded Y	Recorded	X	Y
1	-154	-68	0.1	0	0
2	-156	-69	0.2	-2	-1
3	-155	-71	0.4	-1	-3
4	-154	-73	0.45	0	-5
5	-154	-74	0.5	0	-6
6	-151	-75	0.5	3	-7
7	-146	-73	0.5	8	-5
8	-145	-73	0.5	9	-5
9	-144	-69	0.5	10	-1
10	-155	-73	0.5	-1	-5
11	-159	-71	0.5	-5	-3
12	-166	-73	0.5	-12	-5
13	-172	-73	0.5	-18	-5
14	-177	-75	0.5	-23	-7
15	-176	-75	0.5	-22	-7
16	-180	-75	0.5	-26	-7
17	-178	-76	0.5	-24	-8
18	-179	-76	0.5	-25	-8
19	-172	-77	0.5	-18	-9
20	-158	-69	0.45	-4	-1
21	-151	-65	0.45	3	3
22	-151	-65	0.45	3	3
23	-151	-66	0.45	3	2
24	-150	-64	0.45	4	4
25	-149	-62	0.45	5	6
26	-149	-60	0.4	5	8
27	-149	-58	0.4	5	10
28	-149	-58	0.4	5	10
29	-153	-58	0.4	1	10
30	-154	-60	0.4	0	8
31	-159	-62	0.35	-5	6
32	-163	-64	0.35	-9	4
33	-164	-64	0.35	-10	4
34	-165	-63	0.35	-11	5
35	-167	-66	0.35	-13	2
36	-165	-64	0.35	-11	4
37	-162	-63	0.35	-8	5
38	-157	-62	0.35	-3	6
39	-157	-63	0.35	-3	5
40	-156	-61	0.35	-2	7
41	-158	-62	0.35	-4	6
42	-155	-62	0.4	-1	6
43	-158	-63	0.55	-4	5
44	-161	-64	0.75	-7	4
45	-160	-65	1	-6	3
46	-157	-65	1.3	-3	3
47	-151	-64	1.65	3	4
48	-118	-64	2	36	4
49	-23	-65	2.3	131	3
50	93	-65	2.55	247	3
51	229	-65	2.75	383	3
52	358	-65	2.9	512	3
53	480	-65	3.1	634	3
54	608	-66	3.3	762	2
55	751	-65	3.45	905	3
56	908	-64	3.65	1062	4
57	1115	-63	3.85	1269	5
58	1318	-61	4.05	1472	7
59	1591	-56	4.25	1745	12
60	1878	-53	4.4	2032	15
61	2183	-50	4.6	2337	18
62	2339	-47	4.8	2493	21
63	2568	-45	4.95	2722	23
64	2725	-42	5.15	2879	26
65	2876	-38	5.3	3030	30
66	2984	-33	5.3	3138	35
67	3026	-28		3180	40
68	3454	-7		3608	61
69	448	-1520		602	-1452
70	478	-1697		632	-1629
71	620	2		774	70
72	814	1208		968	1276
73	777	1393		931	1461
74	799	1421		953	1489
75	806	1423		960	1491
76	856	1403		1010	1471
77	867	1438		1021	1506
78	1003	1489		1157	1557
79	1044	1550		1198	1618
80	1050	1670		1204	1738
81	1054	1775		1208	1843
82	1054	1889		1208	1957
83	1048	1994		1202	2062
84	1043	2090		1197	2158
85	1039	2143		1193	2211
86	1026	2214		1180	2282
87	1086	2158		1240	2226
88	841	1905		995	1973
89	744	1748		898	1816

Load vs Strain Analysis

Specimen	Strian Gauge Value		Load	Calculated Variation	
A-70	Recorded X	Recorded Y	Recorded	X	Y
1	-43	258	-0.05	0	0
2	-45	258	-0.05	-2	0
3	-46	259	0.05	-3	1
4	-46	258	0.15	-3	0
5	-47	258	0.25	-4	0
6	-45	255	0.25	-2	-3
7	-39	254	0.3	4	-4
8	-46	256	0.3	-3	-2
9	-42	258	0.3	1	0
10	-53	265	0.3	-10	7
11	-63	275	0.35	-20	17
12	-76	281	0.35	-33	23
13	-67	279	0.35	-24	21
14	-55	269	0.4	-12	11
15	-43	258	0.4	0	0
16	-35	252	0.45	8	-6
17	-34	246	0.5	9	-12
18	-28	238	0.55	15	-20
19	-24	231	0.65	19	-27
20	-17	222	0.75	26	-36
21	7	204	0.95	50	-54
22	21	183	1.3	64	-75
23	38	158	1.75	81	-100
24	58	133	2.1	101	-125
25	83	125	2.45	126	-133
26	125	118	2.7	168	-140
27	162	107	2.9	205	-151
28	193	106	3.1	236	-152
29	226	103	3.3	269	-155
30	264	98	3.45	307	-160
31	292	93	3.65	335	-165
32	334	90	3.85	377	-168
33	372	87	4	415	-171
34	404	85	4.2	447	-173
35	437	85	4.4	480	-173
36	480	78	4.6	523	-180
37	534	66	4.75	577	-192
38	594	51	4.9	637	-207
39	649	36	5	692	-222
40	695	24	5.2	738	-234
41	756	8	5.4	799	-250
42	821	-8	5.6	864	-266
43	883	-28	5.75	926	-286
44	953	-50	5.9	996	-308
45	1017	-73	6.05	1060	-331
46	1071	-91	6.25	1114	-349
47	1123	-106	6.4	1166	-364
48	1195	-117	6.6	1238	-375
49	1247	-127	6.8	1290	-385
50	1305	-142	6.95	1348	-400
51	1369	-150	7.15	1412	-408
52	1424	-162	7.35	1467	-420
53	1476	-172	6.75	1519	-430
54	1372	-169	7.3	1415	-427
55	1459	-189	7.5	1502	-447
56	1516	-205	7.7	1559	-463
57	1575	-219	7.9	1618	-477
58	1625	-228	8.1	1668	-486
59	1693	-244	8.15	1736	-502
60	1739	-252	8.3	1782	-510
61	1792	-265	8.5	1835	-523
62	1846	-277	8.7	1889	-535
63	1917	-290	8.9	1960	-548
64	1988	-304	9.1	2031	-562
65	2079	-321	9.3	2122	-579
66	2168	-334	9.45	2211	-592
67	2257	-349	9.65	2300	-607
68	2364	-365	9.85	2407	-623
69	2475	-379	10.05	2518	-637
70	2593	-396	10.15	2636	-654
71	2724	-414	10.35	2767	-672
72	2859	-435	10.55	2902	-693
73	2992	-460	10.75	3035	-718
74	3127	-490	10.9	3170	-748
75	3246	-531	11.1	3289	-789
76	3379	-579	11.25	3422	-837
77	3562	-635	11.35	3605	-893
78	3738	-712	10.65		
79	3759	-890			
80	98	673			
81	139	689			
82	124	568			
83	103	507			
84	85	470			
85	162	471			
86	233	478			
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Specimen	Strian Gauge Value		Load	Calculated Variation	
E-70	Recorded X	Recorded Y	Recorded	X	Y
1	-210	-556	-0.25	0	0
2	-218	-410	-0.25	-8	146
3	-217	-377	-0.05	-7	179
4	-211	-300	0.25	-1	256
5	-198	-258	0.35	12	298
6	-167	-151	0.4	43	405
7	-149	-95	0.4	61	461
8	-141	-277	0.4	69	279
9	-140	-445	0.45	70	111
10	-146	-609	0.45	64	-53
11	-149	-721	0.55	61	-165
12	-148	-881	0.7	62	-325
13	-140	-983	1	70	-427
14	-103	-960	1.35	107	-404
15	-59	-1119	1.7	151	-563
16	-17	-2040	1.95	193	-1484
17	23	-594	2.2	233	-38
18	54	-543	2.4	264	13
19	82	-557	2.65	292	-1
20	107	-533	2.85	317	23
21	136	-540	2.95	346	16
22	156	-545	3.05	366	11
23	32	-622	3.15	242	-66
24	-56	-640	3.2	154	-84
25	-75	-662			
26	-85	-1093			
27	-94	-1134			
28	-125	-1000		85	
29	-130	-983		80	
30	-133	-980		77	
31	-136	-980		74	
32	-138	-980		72	
33	-139	-982		71	
34	-141	-983		69	
35	-145	-1008		65	
36	-146	-1011		64	
37	-148	-1012		62	
38	-148	-1015		62	
39	-149	-1012		61	
40	-149	-1017		61	
41	-151	-1017		59	
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Load vs Strain Analysis

Specimen	Strian Gauge Value		Load	Calculated Variation	
A-80	Recorded X	Recorded Y	Recorded	X	Y
1	-190	173	-0.2	0	0
2	-212	175	-0.15	-22	2
3	-217	170	0.3	-27	-3
4	-214	168	1	-24	-5
5	-207	166	1.1	-17	-7
6	-187	153	1.15	3	-20
7	-163	148	1.2	27	-25
8	-146	144	1.25	44	-29
9	-133	145	1.25	57	-28
10	-120	146	1.3	70	-27
11	-108	143	1.3	82	-30
12	-93	141	1.35	97	-32
13	-74	143	1.35	116	-30
14	-56	147	1.4	134	-26
15	-40	152	1.45	150	-21
16	-25	156	1.5	165	-17
17	-15	162	1.5	175	-11
18	0	169	1.55	190	-4
19	16	176	1.65	206	3
20	37	183	1.7	227	10
21	59	190	1.75	249	17
22	86	198	1.85	276	25
23	115	208	1.95	305	35
24	148	219	2.1	338	46
25	186	232	2.25	376	59
26	227	248	2.45	417	75
27	271	264	2.7	461	91
28	319	279	2.95	509	106
29	367	297	3.2	557	124
30	417	316	3.45	607	143
31	464	332	3.7	654	159
32	504	348	3.9	694	175
33	545	367	4.1	735	194
34	583	387	4.3	773	214
35	615	404	4.5	805	231
36	646	422	4.65	836	249
37	674	440	4.85	864	267
38	700	465	5.05	890	292
39	728	486	5.25	918	313
40	753	514	5.45	943	341
41	780	542	5.6	970	369
42	809	574	5.8	999	401
43	829	605	5.95	1019	432
44	854	635	6.1	1044	462
45	875	658	6.25	1065	485
46	903	683	6.45	1093	510
47	927	711	6.7	1117	538
48	960	748	6.9	1150	575
49	995	792	7.1	1185	619
50	1039	845	7.35	1229	672
51	1075	892	7.55	1265	719
52	1117	949	7.75	1307	776
53	1159	1005	8	1349	832
54	1200	1056	8.2	1390	883
55	1243	1111	8.35	1433	938
56	1292	1174	8.5	1482	1001
57	1338	1230	8.65	1528	1057
58	1419	1291	8.9	1609	1118
59	1531	1357	9.15	1721	1184
60	1642	1448	9.35	1832	1275
61	1748	1530	9.55	1938	1357
62	1861	1649	9.75	2051	1476
63	1999	1829	9.85	2189	1656
64	2145	2009			
65	2289	2232			
66	2652	2705			
67	183	666			
68	36	433			
69	25	323			
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Specimen	Strian Gauge Value		Load	Calculated Variation	
E-80	Recorded X	Recorded Y	Recorded	X	Y
1	-143	5	-0.25	0	0
2	-144	3	-0.25	-1	-2
3	-146	3	0.2	-3	-2
4	-148	5	0.6	-5	0
5	-147	4	0.95	-4	-1
6	-149	5	1	-6	0
7	-144	4	1	-1	-1
8	-141	-1	1	2	-6
9	-141	-4	1	2	-9
10	-160	-5	1	-17	-10
11	-168	-7	1	-25	-12
12	-175	-7	1	-32	-12
13	-180	-8	1	-37	-13
14	-187	-8	1	-44	-13
15	-192	-8	1	-49	-13
16	-192	-8	1.05	-49	-13
17	-195	-9	1.05	-52	-14
18	-192	-8	1.1	-49	-13
19	-192	-8	1.15	-49	-13
20	-193	-8	1.2	-50	-13
21	-192	-8	1.25	-49	-13
22	-192	-8	1.3	-49	-13
23	-192	-8	1.4	-49	-13
24	-186	-6	1.5	-43	-11
25	-176	-5	1.6	-33	-10
26	-176	-5	1.7	-33	-10
27	-173	-4	1.8	-30	-9
28	-170	-4	1.95	-27	-9
29	-166	-3	2.05	-23	-8
30	-161	-2	2.2	-18	-7
31	-151	0	2.3	-8	-5
32	-149	0	2.45	-6	-5
33	-146	1	2.55	-3	-4
34	-142	1	2.65	1	-4
35	-140	0	2.75	3	-5
36	-138	0	2.9	5	-5
37	-135	-1	3	8	-6
38	-132	-1	3.15	11	-6
39	-133	-1	3.25	10	-6
40	-129	-2	3.35	14	-7
41	-123	-2	3.5	20	-7
42	-116	-3	3.65	27	-8
43	-105	-2	3.8	38	-7
44	-91	-3	3.95	52	-8
45	-69	-3	4.1	74	-8
46	-33	-3	4.25	110	-8
47	-3	-5	4.4	140	-10
48	41	-2	4.55	184	-7
49	84	-7	4.65	227	-12
50	137	-7	4.8	280	-12
51	199	-7	4.95	342	-12
52	277	-7	5.1	420	-12
53	372	-7	5.2	515	-12
54	482	-7	5.35	625	-12
55	644	-7	5.5	787	-12
56	925	-4	5.6	1068	-9
57	1297	-2	5.7	1440	-7
58	1829	1	5.8	1972	-4
59	2483	6	5.9	2626	1
60	2909	12	6	3052	7
61	3125	21			
62	3522	38			
63	3542	55			
64	3459	54			
65	3766	-431			
66	583	-2811			
67	303	-500			
68	268	-97			
69	281	-188			
70	307	-745			
71	300	-731			
72	296	-750			
73	298	-769			
74	297	-784			
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Load vs Strain Analysis

Specimen	Strian Gauge Value		Load	Calculated Variation	
A-90	Recorded X	Recorded Y	Recorded	X	Y
1	-243		-0.45	0	
2	-247		-0.45	-4	
3	-246		-0.3	-3	
4	-242		-0.25	1	
5	-239		-0.25	4	
6	-239		-0.2	4	
7	-237		-0.2	6	
8	-231		-0.2	12	
9	-226		-0.15	17	
10	-220		0	23	
11	-212		0.3	31	
12	-197		0.55	46	
13	-149		0.75	94	
14	-64		0.85	179	
15	-9		1	234	
16	31		1.2	274	
17	73		1.35	316	
18	126		1.5	369	
19	174		1.7	417	
20	239		1.85	482	
21	264		2	507	
22	331		2.2	574	
23	369		2.35	612	
24	443		2.5	686	
25	473		2.7	716	
26	547		2.85	790	
27	561		3.05	804	
28	560		3.2	803	
29	607		3.4	850	
30	613		3.6	856	
31	638		3.8	881	
32	649		3.95	892	
33	672		4.15	915	
34	820		4.3	1063	
35	831		4.5	1074	
36	852		4.65	1095	
37	871		4.85	1114	
38	884		5.05	1127	
39	895		5.15	1138	
40	897		5.35	1140	
41	904		5.55	1147	
42	912		5.7	1155	
43	921		5.85	1164	
44	925		6.05	1168	
45	947		6.2	1190	
46	945		6.4	1188	
47	928		6.55	1171	
48	953		6.65	1196	
49	1200				
50	1166				
51	1126				
52	2073				
53	-313				
54	-318				
55	-213				
56	93				
57	243				
58	-100				
59	-122				
60	-148				
61	-192				
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Specimen	Strian Gauge Value		Load	Calculated Variation	
E-90	Recorded X	Recorded Y	Recorded	X	Y
1	280	44	-0.25	0	0
2	278	44	-0.15	-2	0
3	285	44	0.15	5	0
4	288	45	0.4	8	1
5	282	47	0.5	2	3
6	275	47	0.55	-5	3
7	258	49	0.55	-22	5
8	247	50	0.6	-33	6
9	239	52	0.6	-41	8
10	233	53	0.65	-47	9
11	240	52	0.65	-40	8
12	240	54	0.7	-40	10
13	242	55	0.75	-38	11
14	242	55	0.9	-38	11
15	235	55	1.15	-45	11
16	232	56	1.45	-48	12
17	237	56	1.75	-43	12
18	229	60	1.95	-51	16
19	235	61	2.05	-45	17
20	240	62	2.05	-40	18
21	215	64	2.05	-65	20
22	187	66	2.05	-93	22
23	174	66	2.15	-106	22
24	169	68	2.3	-111	24
25	161	69	2.5	-119	25
26	150	68	2.7	-130	24
27	162	68	2.85	-118	24
28	177	69	3.05	-103	25
29	201	68	3.2	-79	24
30	213	69	3.4	-67	25
31	230	69	3.65	-50	25
32	250	66	3.85	-30	22
33	272	65	4.05	-8	21
34	285	65	4.25	5	21
35	298	66	4.5	18	22
36	314	67	4.7	34	23
37	325	68	4.9	45	24
38	332	69	5.15	52	25
39	344	69	5.35	64	25
40	347	70	5.55	67	26
41	356	71	5.7	76	27
42	367	73	5.85	87	29
43	375	75	6.05	95	31
44	366	77	6.2	86	33
45	370	80	6.3	90	36
46	379	83	6.35	99	39
47	386	85	6.55	106	41
48	366	88	6.75	86	44
49	353	92	6.95	73	48
50	346	96	7.15	66	52
51	340	98	7.35	60	54
52	346	100	7.55	66	56
53	351	100	7.75	71	56
54	352	100	7.9	72	56
55	368	100	8	88	56
56	380	99	8.2	100	55
57	384	96	8.35	104	52
58	411	88	8.5	131	44
59	437	80	8.7	157	36
60	461	69	8.9	181	25
61	486	54	9.05	206	10
62	507	39	9.25	227	-5
63	530	19	9.5	250	-25
64	546	-8	9.7	266	-52
65	560	-38	9.9	280	-82
66	588	-77	10	308	-121
67	625	-120	9.85	345	-164
68	708	-171	10.2	428	-215
69	746	-271	10.4	466	-315
70	816	-367	10.45	536	-411
71	873	-415	10.65	593	-459
72	915	-440	10.8	635	-484
73	1002	-371	10.95	722	-415
74	1195	-264	11.1	915	-308
75	1253	-202	11.15	973	-246
76	1411	38			
77	1520	200			
78	1806	3589			
79	957	11956			
80	-359	26487			
81	-194	25781			
82	-92	25542			
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