ABSTRACT

CHATURVEDI, AWANTIKA. Evaluation of the Non-Stop Tying-in Process. (Under the direction of Dr. Abdel-Fattah Mohamed Seyam and Dr. William Oxenham).

The process of weaving is considered to be the bottleneck of the fabric formation process and has always faced the issue of longest stop times during tying-in and style change that have not seen any technological advancement till date. The purpose of this thesis is to assess the market for a modern-day enhancement in the tying-in process that can significantly reduce the stop time of looms. This new improved process is called/named the Non-stop tying-in process. The study also presents an evaluation of the time taken to perform tying-in conventionally as well as an experimental analysis of warp tension levels during weaving. Both of these studies were of vital importance for successful completion of the goal of this project. The thesis documents the first industrial trial that was conducted using the Non-stop tying-in process, and also gives a detailed account of all the iterations needed to be made to the design of the accumulator, for a smoother and successful adoption of the technology.

Evaluation of the Non-stop Tying-in Process

by
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BIOGRAPHY

Coming from a small-town Allahabad, UP, India, Awantika Chaturvedi is the daughter of Neelanjana and Anil Chaturvedi. She has a sister, Bharati and a brother, Samarth. Awantika attended high school at Bethany Convent school and graduated in 2010. She enrolled at Government Central Textile Institute in 2013, where she studied Textile Engineering with a major in Man Made Fiber Technology. In 2017, she graduated with an honors degree in Bachelor of Technology. Awantika is pursuing a Master of Science in Textiles, with a focus in Marketing at the College of Textiles, North Carolina State University and plans to work in the United States in the future prior to returning to India.

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CHAPTER 1: INTRODUCTION

1.1. Introduction to the research

The process of weaving involves interlacement of warp and weft yarns to form a fabric. The process line if traced back from weaving includes formation of fibers, followed by spinning of the yarns. These yarns then need to be sized in order to be strong enough to withhold stress while being woven. These sized yarns are then drawn in either manually or automatically through the heald eyes and reed to form the weaver's beam. This whole process line has become modernized and automated to a great extent; however, the weaving process still remains to be one of the most intermittent and limited in areas of automation till today, thus, making it the bottleneck of the textile pipeline.

Within the area of weaving and specifically tying-in, very limited technological strides have been made in the most recent years. This research is based on an original study of a newly developed and patented process called “Non-stop Tying-in process” (Seyam, A. Oxenham, W. 2017). this process will help make the weaving process continuous to a large extent and also help in improving weaving efficiency multiple folds by reducing down time of looms by up to 8 hours. This study is presented in three different parts.

The first part discusses the tying-in trials that were conducted during conventional tying-in and while the non-stop tying-in process was used. The section ends with a comparison between the data collected during the two instances. The second section of the thesis addresses one of the most important metrics for the non-stop method, yarn tension. This part also offers a comparison and analysis of yarn tension recorded before and after the non-stop tying-in method was employed. In the third and final section, the research of finding the market potential for the new process has been presented. For this a number of approaches were followed and organizations contacted.

1.2. Introduction to drawing-in and tying-in

Both of these processes are used for preparing a warp beam that used as input to a loom for weaving. The basic difference between these two methods is that drawing-in is done when a new fabric with a different design than the one already running on a loom is supposed to be woven; while tying-in is done when the fabric with the same design as the one on a particular loom, whose warp beam is about to exhaust, has to be woven. The two processes are discussed in further detail below.

1.2.1. Drawing-in

Drawing-in is the process that connects sizing and weaving. The term drawing-in and warp tying refer to the operations involved in preparing the weaver's beam for the purpose of weaving fabrics on the loom. The drawing-in process primarily consists of drawing ends from the weaver's beam through heald eyes of different harnesses and then through the dents of a reed in the order that is determined by the design of the fabric. If a beam is to be worked with warp stop motion on the loom, especially when using closed drop-pins, the ends have to be drawn through these pins before drawing them through the heald eyes and reed dents. Conventionally drawing-in is carried out manually by two persons-one, the “reacher” selects and presents the ends from the beam, and the other, the “drawer” pulls ends through the drop-pins, heald eyes and reed dents. For manual drawing-in operators should be trained well to understand the principles and also work with speed, so as to keep the delays to a minimum.

Over the years semi-automatic and fully automatic drawing-in machines have come into the market. In a semi-automatic drawing in device a reaching-in machine is employed for the purpose of end-finding from the weaver’s beam, thereby reducing the labor requirements from two workers per set to one worker per set. The worker has only to draw the ends as given by the reaching-in machine through appropriate heald eyes and dents in the reed. It is quicker than the manual drawing-in, the quality of work is better, the cost of drawing-in is less, and the floor space requirement for a given size of loom shed is less as compared to manual drawing-in process. However, since the capital investment is more, it is economical only where the volume of work is sufficient to keep the machine fully engaged.

In the case of a fully automatic drawing-in machine, the machine automatically carries all warp ends to the reed hook in proper sequence. The beam is fitted on the stands of the machine provided for this purpose. The warps are fixed between a pair of clamps without disturbing their relative positions. The first warp end is connected with the automatic reaching-in motion and the current switched on. The automatic device then presents to the reed hook all the warp ends one by one on correct rotation. As soon as any warp end is taken off by the drawer, the next end is ready. Further, the machine is provided with mechanism for separating the warp ends that might be sticking together. This will ensure only one end being conveyed to the reed hook at each operation. The operation of the machine is very simple and requires an adjustment when changing over from one count to another. It can be used for all types of textile warps.

1.2.2. Tying-in

Tying-in is primarily used when a fabric is being mass produced, i.e. after the depletion of the warp beam on the weaving machine, if no change in fabric design is to be made then the process of tying-in is employed. The difference between tying-in and drawing-in is that in tying-in the warp yarns do not have to be drawn through the heddle wires, drop wires and the reed again. Instead, the tail end of the warp yarns from the exhausted warp beam are tied to the corresponding yarns of the new warp by the help of an automatic knotting/warp tying machine. This is usually done at the front side of the loom by using the tying-in table and a number of clamps to hold the two sheets of warp yarns taut and in place. Then, the knotted warp ends are pulled through the heddle eyes and reed until the knots are cleared (Hasan 2014).

A small portable robot is used on or off the weaving machine for tying-in. A typical warp tying machine can knot single or ply yarns from 1.7 to 80 Ne (340-7 tex.) made from cotton, wool, synthetic and blends warp. Typical knotting of a knotter is from 60-600 knots per minute (Hasan 2014). The time taken to complete this process depends on the number of warp ends, type and count of yarn, and other secondary factors which tend to retard productivity. The maximum capacity of warp tying machines has remained unchanged for years at around 600 knots/min.

1.3. Purpose of Study

The purpose of this study was to:

- research the market for modern-day tying-in equipment,
- conduct a time study to compare the time taken for the process using the conventional method against the new equipment,
- perform an assessment of the fabric properties that result from the two different ways of tying-in.

The project deals with eliminating the need for stopping the weaving process in order to conduct tying-in. Currently, when the warp beam runs out, the operator stops the process, and the automatic tying-in machine and its table are brought to the loom along with a full warp beam. Setting time, which is conducted by tying-in operators, is required before the automatic tying-in of each warp yarn from the run-out warp beam to its corresponding yarn of the full warp beam. After tying-in, the empty warp beam is taken out of the loom and replaced by a full warp beam. The knots are then passed through different parts of the weaving machines, namely drop wires, heddle wires, and reed. Then the weaving process resumes after many hours of lost production.

1.4. Significance of Study

The time for which a loom stops while conventional tying-in is being performed is almost three hours (could be up to 8 hours in some cases) and to date there have been no technological advancements to lower this loom down time. This study, addressing the non-stop tying-in process, is significant because it introduces and evaluates a completely new method of tying-in that has never been tried before and which promises to increase weaving efficiency/productivity, reduce the amount of warp waste produced during conventional tying-in and also lower the cost of woven products. The findings of this study will contribute to the benefit of weaving companies all around the world. Not only do the findings suggest increase in weaving efficiency but the process is also accompanied with lesser production of warp waste as compared to the conventional tying-in process. Thus, this method also brings about a more sustainable approach that will help weaving companies all around the world save on resources. With increased weaving efficiency the most significant benefit of this method will be an increase in woven fabric production which will benefit weaving companies around the world financially.

CHAPTER 2: REVIEW OF LITERATURE

2.1. Market Research/ New Products marketing

The first step for any new product development is evaluation of the current market. Researching the present scenario of how an industry is working, leads the inventor to the second most basic thing before inventing something new, which is to identify the problem that currently exists in that area. After the broad scope of the market has been explored, it is time to identify any underserved customer needs or in other words, recognition of an area where development is sorely needed and will help aid faster production, increased efficiency and an easier process. An understanding of one's past deficiencies is the first step to a prescriptive solution. Knowing the market's needs and how it is currently serviced provides key information that is essential in developing the product/service and marketing plan. The central task in new product development is to develop those products (characteristics) that deliver desired benefits for consumers. Once all the research and problem finding has been done, the opportunity is identified where by creative thinking and innovation the problem can be solved ("New Product Development," 2017).

The customers for the new tying-in machine would be any textile manufacturing company that conducts weaving operations. Presently with a conventional tying-in machine a loom is stopped for over 3 hours while tying-in is done. This leads to a tremendous loss in production and thus revenue. The whole process-flow in the textile industry has been streamlined to an extent, however the process of weaving remains a batch process, where looms are brought to a stop every time a new beam is being installed and every time a style change in the fabric is done. The weaving process is also the slowest in the whole fabric formation procedure. Thus, a problem was identified and creatively handled by coming up with a process innovation. This innovation essentially uses the same machines and methods however the procedure of carrying out tying-in has been modified from the current techniques while also employing some additional machinery. This process improvement will help looms run continuously thereby increasing weaving efficiency as well as production.

For successful commercialization of new products, studies have called for more and better marketing research and marketing efforts (including selling and promotion efforts), careful product positioning, more effective concept testing, and better test marketing. Also, a need for better evaluation was noted, including early screening of new product proposals. Often new product innovation fails because the products developed either was a "better mousetrap no one wanted" (an innovative product that did not serve a market need, 28 percent of cases), followed by the "me-too product meeting a competitive brick wall" (similar to competitors' products with no differential advantage, 24 percent of cases) (Cooper, 1983). In almost two-thirds of the cases, a lack of marketing research skills or personnel was thought to have contributed significantly to the failure, while the detailed market study phase was the most poorly undertaken activity of the new product process. Again, this research points to a lack of a market and marketing orientation as the culprit in industrial new product development.

For identifying the factors that lead to a successful launch of a new product, several researchers have studied several new product success stories to identify what characteristics they shared. New product innovations can be either “market pull” type or “technology push” type. An extensive descriptive study of 567 successful innovations showed that most were market-derived (market pull) ventures and only 21 percent were technology push (Cooper,1983). Other factors included internal sources of information which were most important to the innovation process, pointing to the need to foster internal communication. External information via unstructured channels also played a key role.

Successful new product development is fundamentally a multidisciplinary process. Findings have demonstrated that the importance of cooperation between specific functional dyads (i.e., marketing - R&D; R&D - operations; operations - marketing) varies by time (i.e., early vs. late stages), and by the level of innovativeness (i.e., new-to-the-world vs. modifications) associated with the new product being developed (Olson, Walker, Ruekert, & Bonner, 2001).

While several studies have been carried out to establish factors for successful developments and marketing of new products, it is rarely the case of an entirely new product and often incremental products. Thus, the question arises whether the development of really new products require a different approach from that of incremental new products. Four sets of New product development activities—strategic planning, market analysis, technical development, and product commercialization—are key determinants of new product success for both really new products and incremental products. However, strategic planning and business and market opportunity analysis activities play contrasting roles for the two types of products. Working to improve proficiency in business and market opportunity analysis may be counterproductive for really new products, but it can increase the profitability of incremental products. Conversely, improving the proficiency of strategic planning activities has a positive effect on the profitability of the really new products, but it has a negative effect for the incremental products. Overall, the really new products in the study surpass the incremental products in meeting profit objectives (Song X. Michael & Montoya-Weiss Mitzi M., 2003).

For commercialization of any product new or incremental, along with R&D and marketing, firms combine resources and utilize their relations in order to ensure the success of their innovations. The theoretical basis combines literature on innovation, industrial networks, and innovation networks. An innovating firm needs resources to engage in customer education, distribution, marketing communication, relationship mediation, and credibility building when moving from R&D tasks to commercialization tasks. To acquire these resources, the firm needs to experience changes in network relations. Accordingly, the innovating firm needs particular commercialization competence in terms of accessing, mobilizing, and organizing relational resources (Aarikka-Stenroos & Sandberg, 2012). Because the innovating firm requires different resources for commercialization than for R&D, it needs to renew its existing relations or create completely new ones; also, in commercialization, firms need the ability to access and mobilize the necessary relational resources. Commercialization, particularly, sets up substantial challenges in managing network relations (Aarikka-Stenroos & Sandberg, 2012).

Commercialization of new products come with a lot of challenges that the firm has to face. Successful commercialization of new technologies is the riskiest and most rewarding form of new product development activity. New technologies are often commercialized using innovative interfaces that determine how consumers interact with a new product to obtain its functionality. Consumers' perception of uncertainty about the performance of a novel interface is a key issue in the acceptance of new products involving new interfaces. Specifically, when firms commercialize a new interface, they face two major challenges: First to identify the optimal functionality for the new interface, and second, to effectively communicate with consumers in order to reduce uncertainty about the performance of the new interface and increase adoption intentions (Ziamou Paschalina (Lilia), 2003).

2.2. Iterations in new product development

In a study conducted for the Harvard Business Review titled “The New Product Development Game” by writers Hirotaka Takeuchi and Ikujiro Nonaka two different approaches towards developing new products are discussed. The authors claim, “new emphasis on speed and flexibility calls for a different approach for managing new product development". Their study talks about how the traditional sequential, or "relay race," approach to product development may conflict with the goals of maximum speed and flexibility. Instead they suggest a holistic or "rugby" approach wherein a team tries to go the distance as a unit, passing the ball back and forth. Such an approach may better serve today's competitive requirements (Takeuchi and Nonaka, 1986). The older sequential approach towards developing a new product was given the name 'relay race' because the product development process moved like that, with one group of functional specialists passing the baton to the next group. The projects would move on sequentially from phase to phase: concept development, feasibility testing, product design, development process, pilot production, and final production. Under this method, functions were specialized and segmented: the marketing people examined customer needs and perceptions in developing product concepts; the R&D engineers selected the appropriate design; the production engineers put it into shape; and other functional specialists carried the baton at different stages of the race (Takeuchi and Nonaka, 1986). However, under the rugby approach, the product development process is an infused process, and results in the constant interaction of a handpicked, multidisciplinary team whose members work together from start to finish. Rather than moving in defined, highly structured stages, the process is born out of the team members' interplay (Takeuchi and Nonaka, 1986). "A group of engineers, for example, may start to design the product (phase three) before all the results of the feasibility tests (phase two) are in. Or, the team may be forced to reconsider a decision as a result of later information. The team does not stop then but engages in iterative experimentation. This goes on even in the latest phases of the development process (Takeuchi and Nonaka, 1986)". In figure 2.1 the different approaches and the way they witness interaction between teams is shown visually, with type A showing the sequential, old or relay race method and type B and C depicting the newer Rugby approach.

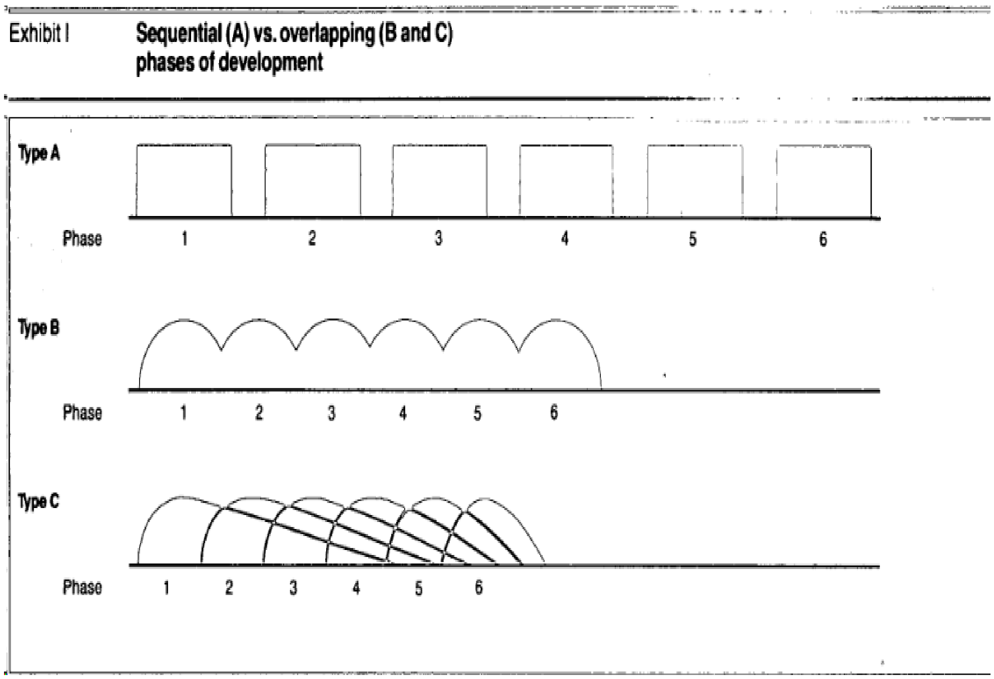

Figure 2.2. Different approaches to new product development, (H. Takeuchi, 1986)

In their study the writers also talked about how companies can make a smooth transition from the traditional ways to newer methods. They suggest that companies need to adopt a management style that can promote the process. “Executives must recognize at the outset that product development seldom proceeds in a linear and static manner. It involves an iterative and dynamic process of trial and error. To manage such a process, companies must maintain a highly adaptive style (Takeuchi and Nonaka 1986)”.

Some studies research the process that following a products development i.e. the trial stage. In the trial stage for a newly developed product a number of redesigns (minor/major), changes or additions might have to be made depending on how the trial goes. Thus it can also be said that in a way product development processes manage risk partially through iterations, which are controlled, feedback-based redesigns (Unger and Eppinger 2011).

Small iterations may include minor changes to components, while large iterations may include marketing feedback that changes the overall design. “Product development processes also manage risk through reviews, which are gates or checks between development stages that are meant to confirm adequacy. Strict reviews prevent further design until early work is finalized, while flexible reviews allow more parallel work (Unger and Eppinger 2011)”.

In their paper titled ‘A dynamic model for managing overlapped iterative product development’, Jun and his team describe and simulate the rework process in the form of *Rework due to development errors* and *Rework due to corruption* (Lin et al 2008).

Product development, even for derivative products, is a process with much uncertainty. Consequently, many tasks are incorrectly done in the completion and rework processes. These tasks are termed as *Development Errors* (DE_s). *Rework due to development errors* refers to rework or rectification of DE_s which are identified through review and testing activities (Lin et al 2008).

Rework due to corruption refers to rework or rectification when the change of tasks in an upstream phase corrupts the relevant tasks in the downstream phases, whether the downstream tasks are done correctly or not. In other words, some tasks need to be reworked because they start on incorrect information from upstream phases (Lin et al 2008).

2.3. Advances in weaving

Through the years, technology concerned with weaving has seen many major developments. From the 18th century drawlooms operated by hand for weaving silk, to the present day fully automated and computerized air-jet and water-jet looms, the woven fabric saw numerous new technologies. This major shift happened slowly and over a large span of time, and it was spurred by some of the greatest discoveries and innovations that this world has seen. To begin with, manual work was replaced by machine production, and the central source of energy to run these looms was the steam engine. Further developments have been categorized and discussed as follows:

Yarn supply

Soon the handlooms were replaced by shuttle looms, wherein a shuttle took the weft from between the shed, but here the weaver had to periodically stop the loom and remove the shuttle to replace the yarn on the spool held in the shuttle. The weaver then started the weaving machine up again.

Then came a drum magazine retrofitted on the loom, that could help change the weft spool automatically. One invention comprised four boxes arranged one above another, after the style of the drop box, the loom continued weaving until all the four shuttles were empty, when it would stop for a further supply of four shuttles. In 1840, Charles Parker invented a motion in which there were two boxes side by side. John Smith, in the year 1844, invented a shuttleless loom, in which the weft was inserted through the shed by a forked rod, the picks being in pairs throughout the piece (Darbyshire, 1949).

Shedding Mechanisms

One of the earliest shedding mechanisms used in weaving looms was the Tappet shedding mechanism. In this shedding system a motion of tappets and cams cause the formation of sheds by raising and lowering shafts. However, the negative point of this system was that the arrangement occupied so much space that only eight heald shafts could be accommodated and thus this system limited the weave repeat to a maximum size of eight. Only plain weaves, simple twills and sateen/satin weaves could be produced with this system.

This mechanism was followed by the development of the Dobby Shedding mechanism. This system could control a number of harnesses and produce weaves with bigger repeat sizes. Today, though the crank and cam shedding motions are still mainly used on high-speed air-jet and water-jet weaving machines for weaving fabrics with plain and basic weaves, there has been widespread use of negative dobby on air-jet and water-jet looms in industry, the use of rotary dobby (i.e., positive dobby) with air-jet looms has widened even more in recent years, due to the increase in rotary dobby running speeds (Eren, Ozkan, & Karahan, 2005).

The latest and most advanced shedding system is the Jacquard, herein there are no shafts, instead a harness consisting of as many cords as there are ends in the warp sheet connects each end individually to the Jacquard machine situated high above the loom. Thus, each warp end is individually controlled and can be weave independently, this results in the option to create intricate weaves with patterns and huge repeat sizes to be woven.

Insertion Mechanisms

The first shuttleless loom used a projectile weft insertion method and was called projectile loom. The first Sulzer machine with a reed width of 216 cm, exhibited at ITMA 1955 at Brussels, had a maximum speed of 280 picks/min (Hari & Behera, 1994). The rapier loom was another upgrade from shuttle looms to the world of modern weaving system and shuttleless weaving. Rapier looms were designed to replace the old shuttle looms without any major changes to the existing infrastructure (Chummar & Kuriakose, 2013).

Almost at the same time as projectile looms, came the Airjet looms which are, in the present day the most widely used looms for mass production of a wide range of fabrics. “However, the real breakthrough came around 1968 when airjet looms running with relay nozzles, spaced at intervals of 40-80 cm, across the entire sley were available (P. Hari & B. Behera, 1994)”. The water jet loom is probably the most efficient machine for weaving 100% hydrophobic filament yams among all available systems. Next to the multiphase 100m, this technology offers the highest weft insertion rate and minimum noise. Some manufacturers have developed machines which are operating at about 2600 m/min (Hari & Behera, 1994).

Even after so many developments in weft insertion methods, there is still no single method that does not have a negative side. The air-jet method is known to offer the highest rate of weft insertion, but this comes at a cost of high energy consumption (12 kWh) required for processing of compressed air. The air-jet weaving machine combines high performance with low manufacturing requirements, because differently from rapier and projectile machines, the filling medium is just air and no mechanical parts are directly involved in the weft insertion process. It has an extremely high production rate up to 1,100 weft insertions per minute and it covers a wide range of processing yarns like spun and continuous filament yarns. However, the main drawback regarding of the technology is the very high energy consumption due to the compressed air usage which is required during the weft insertion process (Grassi, Schröter, Gloy, & Gries, 2016).

On top of that, air jet weft insertion method is not suitable for processing different kinds of yarn materials, for example a flat or heavy yarn is difficult to be processed via air jet weaving

(Jordan et al. 2018). After air jet weft insertion method, Rapier weaving is the most versatile method since it allows for a gentle transportation of any weft yarn material. However, due to heavy masses of moving parts and the acceleration and deceleration required for the rapiers, the productivity achieved through this method is limited. The energy consumption for rapier weaving machines is about 6kWh which is not as high as the air-jet machines (Jordan et al. 2018). Projectile weaving consumes the least energy (about 4 kWh) and also offers insertion rate same as that for rapier weaving, however, due to the high acceleration at initiation of movement, a high impact load is imparted to the yarn, thus, only those yarns that have a good value of tensile strength can be used for weft insertion via projectile machines (Jordan et al. 2018). Newer and innovative method of weft insertion are being developed to combine the advantages and overcome the deficits that arise from the existing methods. One such weft insertion is based on the principle of using a magnetic force for the controlled transport of the weft yarn. “The new method allows a potential energy saving of about 60% compared to a conventional air jet weaving machine” (Jordan et al. 2018).

With the advent of the Industrial Age, rapid developments in machinery and textile manufacturing techniques have advanced the science of textiles in the past one hundred years more than in all of previous history (Kamiya et at., 2000). Today's sophisticated CAD/CAM controlled machines result in high-speed, low-cost and large-volume textile production (Kamiya et al, 2000). Apart from the various weft insertion systems that were developed, the other striking features among the developments in weaving have been the higher production speed, microprocessor applications, information technology, quick-style-change system, energy conservation, safety measures, etc. (Hari & Behera, 1994).

Another price that one must pay while increasing weaving speed is decrease in weaving efficiency. As the machine speed increases, the probability of more and more yarns breaking rises, leading to more frequency of loom stoppage. Thus, although the speed has been increased, the multiple times that the loom is stopped leads to decrease in overall weaving efficiency. Although air-jet weaving's high productivity reduces energy cost per production unit to below that for fly-shuttle looms, energy costs and weaving efficiencies are vital issues in design, marketing, and application.

2.4. Technological advancements in the areas of tying-in and drawing in

2.4.1. Drawing-in

The Drawing in process has evolved a lot since manual threading of warp was performed through the loom parts. It began with the development of the semi-automatic drawing-in machine. This machine has a reaching-in machine that is installed for bringing singularized warp ends from the warp beam. Thus, the labor required from two operators is reduced to one in this case. Once the reaching-in machine delivers a warp end, one operator is required to thread that end through the heddle wire and reed dent.

One of the greatest and most remarkable innovations in this area has been that of the fully Automatic Drawing-in machine. These automatic machines are more prominently used in companies that produce a wide variety/range of different fabric styles. Because as mentioned before, Drawing-in is done usually to facilitate style change. In case a company sticks with just limited styles of fabric production, then they are more likely to just have manual Drawing-in.

Both kinds of these machines, the semi-automatic and fully automatic reduce the need for labor, are quicker than manual workers, and leave less scope for faults, thus, making the quality of work better. However, since the cost of such an equipment is very high, the return on investment on the machine only proves to be economical if it is kept fully engaged at all times.

The fully automatic Drawing-in machine is a computerized machinery that can simultaneously perform drawing and denting according to the draft plans that are already fed into the computer. It can also draw the threads through the drop wires or pins that facilitate the warp stop motion. The speed at which these machines work is very high, almost in the range of 130 ends per minute, and there are adjustments available to increase or decrease the drawing-in speed depending on the yarn characteristics and weaving requirements (Kushwaha, 2017).

The warp beam for this machine is placed at the back side and the warp is brushed up and placed at its proper place. The harness frames and drop pins are fitted in the middle section of the machine. The front side of the automatic Drawing-in machines is fitted with the reed, and the first dent in the reed through which the warp yarn is supposed to be drawn-in is in line with a hook. The computer fitted on to the machine is fed all the relevant data regarding the draft plan and dent plan which dictate the order and pattern in which each warp thread is drawn in through different harness frames and reed dents (Kushwaha, 2017). As soon as the machine is turned on, the hook in front of the reed dent, moves forward through the reed, heald eye and drop wire to catch the first thread to be drawn-in, on its return journey backwards, it threads that warp end through the three loom components (Kushwaha, 2017). Once the warp thread is into the three parts, heald and drop wire are moved into their respective strips, and every time a cycle warp thread being drawn takes place, the respective heald and drop wire are placed in their strips according to the program that is already fed into the computer (Gironi, 1990). Once the drawing-in of every warp end of the beam is complete, the warp beam is taken to the weaving facility for further processes. Although the machine saves a lot of time, and prevents errors, it’s still very expensive and just a few of the big mills use it.

Switzerland-based company Stäubli AG is one of the biggest players among companies that manufacture the Automatic Drawing-in machine. Its reports say that automatic drawing-in machines for the weaving harness have long helped weaving mills around the world stay competitive. Automatically drawn-in warps are characterized by zero defect and high quality, and they are available as required for production in a fraction of the time compared with manual drawing-in (Rupp, 2010).

Stäubli has an upgraded automatic drawing-in machine that has been built on their previous model called Delta. This upgraded automatic drawing-in machine named Safir is an innovative development that combines components of the existing machine Delta and the very efficient Opal leasing machine, thus, rendering highest ever opportunities for flexibility in warp drawing-in and newer opportunities regarding flexibility (Rupp, 2010).

The Opal drawing-in machine is the most efficient to draw-in a direct warper having several different color stripes, this is so because it can lease several warp sheets automatically. Since Safir was introduced at ITMA 2007 in Munich, Germany, several upgrades have been made on it and the machine can now be configured to draw in one or two warp beams, each having up to eight thread layers. An optic camera system is installed that records and checks every warp yarn drawn during each cycle and thus ensures that no two yarns are drawn simultaneously and that a yarn of the wrong color is not chosen. A camera system checks the yam being drawn in during each cycle and ensures against drawing-in of double threads or threads of the wrong color (Rupp, 2010). Thus, the updated model Safir comes with double yarn detection system and color recognition. This machine is easily able to separate warp yarns individually by the help of the vacuum gripper system that was earlier introduced by Staubli in their Opal leasing machine.

With Safir it is also possible to program up to 28 different harnesses to be woven from. Because of the machines flexibility each different harness can be handled freely just by programming. In addition, it also has a feature that allows the use of two different kinds of drop wires for the same harness. This feature comes especially handy during terry fabric weaving because the weight of the drop wires for the upper beam and ground and pile threads tends to experience differences, and by using these two different kinds of drop wires, this difference in weight can be avoided. The machine has also been innovated to provide the best ergonomics and easy to do operations by the installation of a color touchscreen on the machine (Rupp, 2010), (Wilhelm, 1991).

As Staubli further innovated the Safir, they developed different versions of it for different types of yarns and different styles of fabrics. Safir comes in four different versions called S30, S40, S60 and S80. The last two versions are equipped with color management system that can detect and thus correct the sequence of color in the warp yarns. It has a storage area that is used to store those color of yarns that are not in use for the moment. These versions also come with a technology to recognize the yarn structure, like the twist direction and the denier of the yarns. While the S30 and S40 can handle a maximum of 12 harnesses, they are movable. On the contrary the S60 and S80 can handle up to a maximum of 28 harnesses and are stationary. Since S60 and S80 come color recognition, they are the most suitable for performing drawing-in of warps with intricate color patterns and multi layered warps. While the S30 is most used for technical and filament yarns, S60 is suitable for basic fabrics, fabrics for printing and bed sheets/bedlinens.

2.4.2. Tying-in

The process of Tying-in is widely used these days in mills that produce large quantities of a similar fabric/style. For such a case, it is not required for the warp quality to be changed often.

The new warp supposed to be tied-in should have the same number of ends as the beam that ran out of warp, the same count of healds and reeds, and the order in which the new warp yarns are threaded through the machine parts should remain identical. In case the warp is striped or has a pattern, the new beam should have the exact same pattern. Since the time when tying-in was performed by hands manually till today some phenomenal innovations have taken place. The biggest of which is the development of the warp tying/knotting machine. This small machine is able to automatically knot together corresponding ends of warp threads from the two warp beams. The sequence of operations carried out on these machines is similar to that followed in the case of manual twisting in. The operations of selection and knotting of the ends, cutting the tail end of the knotted thread and stopping the machine in the event of a thread found missing or broken are performed mechanically and automatically.

In the current textile industry Tying-in has become a very vital function. Not only is it required that the process is accurate, it also has to be the most efficient in order to minimize the loom downtime, because the longer the loom is stopped the lesser weaving efficiency is achieved (Rozelle, 1994). Warp-tying is thus a cost factor in the weaving mill.

Stäubli reports its Magma warp-tying machine is especially suitable for tying coarse yarns. A patent-pending system that works without yarn-specific settings enables separation of threads to be tied at the lease, which considerably simplifies operation and changing from one application to the next. A built-in camera system monitors the separation of the threads, thus eliminating doubled threads. Magma also can be set easily to tie double knots, and therefore can tie even very slick yams reliably, according to the company. The Magma warp-tying machine for coarse yarns complements Staubli's Topmatic tying machine line. The machines feature a new, patented separating system that reliably separates threads from the lease completely without using thread -

specific separating elements and without making special adjustments. Optical sensors check every separated yarn pair before tying, thus preventing a false double yam from being tied. The fault can be corrected simply. Depending on yam material, single or double knots can be tied, as selected by a simple push of a button. Optimization of the tying rate is accomplished using the adjustment wheel.

Magma can tie a range of yarns including wool, cotton, linen and other staple yarns, as well as mono and multifilament, polypropylene ribbons, and many other yarn types. The yarn count for staple fibers ranges from Ne 0.3 to 50 for warps with 1:1 lease. The machine comes equipped with an optical double-yarn sensor, and single or double knots can be selected easily. The length of knot ends is variable, with a minimum of 5 mm. The tying frame can be used on all Stäubli type TPF3 tying frames, and easy maintenance is guaranteed, with only regular lubrication needed (Rupp, 2010).

2.5. The Non-Stop Tying-in Process

The newest innovation in the area of Tying-in is that of a Non-stop tying-in process. As is evident the whole-time conventional tying-in is performed on a loom, the loom is stopped and remains like that for a minimum of 3-4 hours. This leads to weaving still being a batch process. This newest innovation promises to help a loom continue operation even while tying-in is being performed on it. This can be done by the help of an additional warp tail that is present at the base layers of the warp beam which in the prototype was retained by the aid of a spring road. Once the warp on the beam nears extinction, this tail warp emerges and is accommodated on an accumulator which is present at the back side of the loom. This whole time the beam still has enough warp to continue running. As the warp is being accumulated (and ultimately fed to the loom) the warp from this tail warp is tied to the new warp sheet by the help of the tying-in/knotting machine. Thus, through this whole operation the loom never stops and tying-in is facilitated at the back side of the loom by the help of the tail warp and the accumulator ("Non-Stop Tying-In Process — U.S. Patent Application Number 62451851 | Textile World," n.d.).

This innovative technique of Non-stop tying-in, will to a great extent help in increasing the weaving efficiency and also make the weaving process more continuous. As we move ahead, and the industry keeps on growing, newer innovations might come up that will certainly be embraced if they improve the efficiency of the process.

2.5.1. Time-Study of Tying-in process

Not a lot of time studies for the tying-in process have been done in the past, thus making the literature in this area scarce. With regards to the non-stop tying-in process itself, a time study was conducted at the Weaving Lab at North Carolina State University's (NC State's) College of Textiles. In this study the total time from loom beam run out to the recommencement of weaving with the new warp was 196 minutes. To precisely get the time for each task, a video capturing system was used. The video was streamed to capture the beginning and end of each event.

This time study revealed that there are numerous tasks required before and after the actual tying-in task. The tying-in process (task 22) took 77 minutes to complete. The preparation for the tying-in tasks (1-21) took 98 minutes to perform while the tasks (23-27) conducted after tying-in took 21 minutes (shown in figure 2.2) ("Non-Stop Tying-In Process — U.S. Patent Application Number 62451851 | Textile World," n.d.).

However, a point of concern here is that in this study the number of ends of warp were low, and in an industry setting the warp beam could be of a way higher warp density which would take even more time to complete the actual tying-in. With such a high number of warp yarns, it is expected that the stop time to conduct tying-in process and its preparation will be much higher.

Task Sequence	Task	Duration (min)	Task Sequence	Task	Duration (min)
1	Pulling depleted warp from old beam	10	15	Straightening and checking beam-warp's lease strings	9
2	Securing loom-warp ends (clamping)	1	16	Unrolling loom-warp	1
3	Cutting loom-warp ends	2	17	Straightening and combing loom-warp	7
4	Rolling loom-warp	2	18	Clamping loom-warp to tying-in table	3
5	Cleaning old beam	3	19	Cutting Extra Warp length of loom-warp	1
6	Releasing old beam	1	20	Disposal of the cut warp from previous step	1
7	Installation of new warp beam	30	21	Straightening and checking loom-warp's lease strings	5
8	Unrolling warp from new warp beam	1	22	Tying-in	77
9	Warp let-off from new beam	1	23	Removing tying-in machine and table	5
10	Straightening and combing warp from new warp beam	14	24	Straightening warp (winding beam)	3
11	Clamping warp from new beam to tying-in table	3	25	Fixing failed knots	2
12	Cutting extra warp length from new beam	1	26	Brushing knots	1
13	Disposal of extra warp cut in the previous step	1	27	Passing knots through weaving machine elements (drop wires, heddles, and reed dents)	10
14	Installing tying-in metal bars for loom-warp layer	1	Total Time, min		196

Figure 2. 3 Time study for conventional tying-in done at NCSU (A. Seyam & W. Oxenham)

2.5.2. Approach

This project deals with eliminating the need for stopping the weaving process in order to conduct tying-in. Currently, when the warp beam runs out, the operator stops the process, and an automatic tying-in machine and its table are brought to the loom along with a full warp beam. Setting time, which is conducted by tying-in operators, is required before the automatic tying-in of each warp yarn from the run-out warp beam to its corresponding yarn of the full warp beam. After tying-in, the empty warp beam is taken out of the loom and replaced by a full warp beam. The knots are then passed through different parts of the weaving machines, namely drop wires, heddle wires, and reed. Then the weaving process resumes after many hours of lost production.

The recognized advantages of the project are to increase weaving efficiency/productivity and reduce the cost of woven products. This will afford U.S. woven fabric manufacturers a competitive advantage and potentially increase the number of jobs in weaving and its allied industries, which is in line with the target of the Walmart U.S. Manufacturing Innovation Fund.

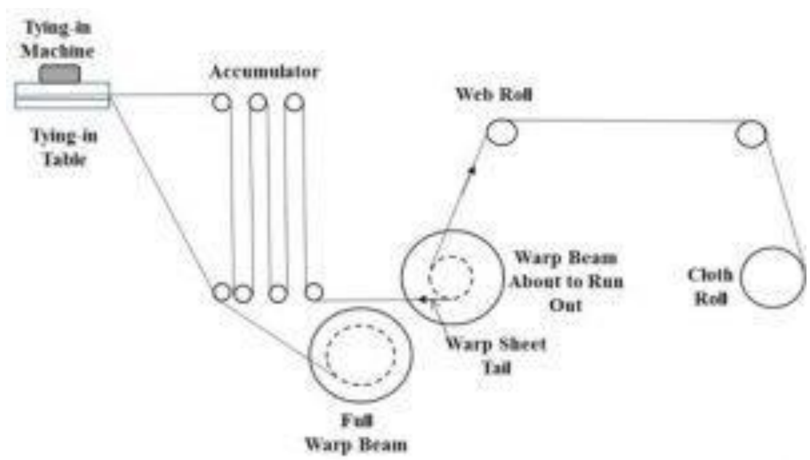

Figure 2. 4 Concept of non-stop tying-in process, (A Seyam & W. Oxenham, 2017)

The problem to be addressed is that in order to provide new warp sheet, the weaving machine needs to be stopped, to allow for knotting of yarns from the new warp sheet to the end of the run-out warp sheet, and this essentially renders weaving as a batch process. To continue weaving during the tying-in process and achieve the objectives of the project, two developments are required:

1. Develop a loom beam winding procedure, at the sizing or warping process, to create a warp beam with tail that will be available for tying-in before warp beam runs out,
2. Develop a warp sheet accumulator to store the warp tail while the weaving machine is forming the fabric from the main warp sheet.

The warp tail length, which depends on the weaving speed and pick density — or fabric take up speed — must be sufficient to allow time for the tying-in and its associated procedures. A schematic of the concept of non-stop tying-in process is shown in Figure 2.3. The figure shows as the warp beam is running out, the tail will unwind and become available for connecting to yarn on the replacement beam. As it can be seen from figure 2.3, the warp sheet tail is fed out through the accumulator's rollers into the tying-in table. The sheet of the full warp beam is also fed into the tying-in table. The yarns of the two warp sheets will be joined, and any excess warp sheet length will be accommodated by the spread of the moveable rollers of the accumulator, which is also part of a control system to ensure uniform tension. When the process is completed, the full warp beam will replace the empty warp beam. Then both tying-in machine and the accumulator are moved out to storage or to the next weaving machine for another tying-in procedure. To design and build non-stop equipment and procedures, it was decided to conduct tying-in time study to capture the time of every task performed during the entire tying-in process, including preparation for tying-in, tying-in, and post tying-in tasks. This will enable the determination of tasks that could be streamlined during the formation of tailed warp beam and non-stop tying-in process as well as design the equipment for ergonomic purpose, which will lead to overall improvement in weaving efficiency.

2.5.3. The Non-Stop Equipment/Prototype development

A proprietary passive warp storage (accumulator) as a first prototype, was designed and built at NC State's machine shop. It was designed to work with 20-inch-wide CCI sample loom available at the College of Textiles. The word passive here indicates that there is no warp sheet tension control, rather the warp sheet tension is controlled by rollers and dead weights. This is a simple flexible prototype to be used for developing the final, more sophisticated solution. The purpose of the first prototype is to study the operator/machine interaction, improve ergonomics and reduce process time and lead to design of an active prototype with tension control. Figure 2.4 shows the warp accumulator disassembled and figure 2.5 shows it assembled. The system was designed in two parts to allow disengaging the system from the warp sheet after completing the tying-in process using four quick release clamps for quick disassembling/assembling. Figure 2.5 also shows the different parts of the warp accumulator. The number between parentheses indicates the quantity of each part.

Figure 2. 5 **Warp sheet accumulator disassembled and assembled** **(A Seyam & W. Oxenham, 2017)**

Figure 2. 6 Parts of the accumulator (A Seyam & W. Oxenham, 2017)

1 Movable roller (1), 2 Quick release clamp (4), 3 Accumulator frame (1), 4 Movable roller guides bracket (2), 5 Fixed roller (1), 6 Fixed roller bearing (2), 7 Floating roller guide bracket (1), 8 Floating roller (1), 8 Wheels (6)

A warp beam support, which is needed to work with warping machine to form wrap beam with tail, was also designed and built. This equipment supports a warp beam that has the tail warp sheet with required length. The beam is termed tail beam. The support is a frame with two bearings to allow unwinding the tail to form the final beam with tail using the warper. This is also a passive system. A more sophisticated system for the accumulator was designed and built by a collaboration with Menzel, a machine manufacturing company based out of Spartanburg, South Carolina. This accumulator has a tension control and positive feed and took X months to be Manufactured after the design was finalized. Once the system was ready the designers and leaders of the project made a visit to the Menzel plant in Spartanburg, SC and witnessed an experimental trial which used sheets of plastic in place of the warp sheet. Each component of this machine was shipped to P&A

in disassembled form after which a service technician from Menzel (Mr. Tony Melton) visited the plant in Roxboro and along with the help of another mechanic carried out the job of assembling the accumulator.

CHAPTER 3: TYING-IN TRIALS

3.1. Introduction

Tying-in is used when a fabric is being mass produced. In other words, when a warp beam runs out, and the same fabric production is to be continued with no change in design, then tying-in is used. Tying-in is often used in weaving mills where the quality of warp is not often changed. Some examples of woven fabrics and woven end products that are mass produced and require tying-in often are airbag fabrics, paint brush fabric (for paint rollers), bed sheet fabrics, fabrics for mattress cover, car upholstery, shower curtains, window shades, parachute and ballooning fabrics, sleeping bag fabrics and also towel or pile fabrics.

The tying-in process can be used only where the new warp is identical to the old warp in respect of total number of ends, counts of yarn, and the order in which the ends are to be drawn through the healds and reed. If tying-in is to be performed for striped fabrics, then the pattern of the stripes should be identical as well.

Both stationary and portable machines are available for carrying out the process. In this process the tail end of the warp from the exhausted warp beam is tied to the beginning of the new warp, usually with the use of an automatic knotting/warp tying machine. The sequence of operations carried out on these machines is similar to that followed in the case of manual tying in. The operations performed are:

a) selection of two warp yarns- one from the exhausted beam and the corresponding yarn from the new beam,

b) knotting of the ends,

c) cutting the tail end of the knotted thread

d) stopping the machine in the event of a thread found missing or broken.

An automatic tying-in apparatus has the following parts that allow it to perform the necessary functions (Kushwaha n.d.).:

a) A carriage on which the tying apparatus is fitted.

b) Selector needles for picking up threads from the old and new warps one by one in the proper order.

c) Thread carrier for carrying the threads picked up by the selector needles for the next operation of knotting.

d) A knotting unit for knotting the threads picked up by the thread carrier.

e) A shearing mechanism for cutting the tail end of the knotted threads.

f) A traverse motion for effecting advance movement of the carriage carrying the tying apparatus.

g) An electric lamp for providing additional light for watching the performance of the important parts of the apparatus and also the parts of warp situated immediately near the apparatus.

h) A hand wheel for operating the apparatus manually at the start, or for inspection purpose

i) A driving unit, consisting of a small electric motor with necessary arrangement for adjusting the speed.

The time taken to complete the tying-in process depends on the number of warp ends, type and count of yarn, and other secondary factors which tend to retard productivity. The capacity of warp tying machines has remained unchanged for several years at around 600 knots/min.

3.2. Methodology

3.2.1. Conventional tying-in

This tying-in was carried out at a weaving company called P&A Industrial Fabrication LLC, situated at 1841 N Main St, Roxboro, NC 27573. The study was done at a rapier loom (no. 28) that had been manufactured by a Belgian textile machinery manufacturer Vandewiele. All looms at P&A were made between 1982-1985 and these were specialist looms for weaving pile fabrics for paint roller covering., which as such typically had three warp beams (one ground and two pile). The fabric style being woven on the loom was PB410-50. The warp beam had a total of 6480 warp yarns that were 2-ply yarn, with each ply 150 denier. A tying-in operator conducted the whole process while each action required was timed and pictures and videos were taken to capture every step.

The total time recorded for completion of the project was 369 minutes (6 hours, 3 minutes). This time study revealed that there are numerous tasks required before and after the actual tying-in process, which itself only took 35 minutes to complete. The preparation for the tying-in took 154 minutes to perform while the tasks conducted after tying-in took 180 minutes. To precisely get the time for each task, a video capturing system was used. The video was streamed to capture the beginning and end of each event.

The photos taken during the observance of the traditional tying-in process were ordered according to the sequence in which the process took place. Some of the photos taken to capture the process are shown in figures 3.1-3.14.

Figure 3.1. Pulling depleted warp from the old beam

Figure 3.2. Empty beam

Figure 3.3. Warp waste produced from the depleted beam

Figure 3.4. Weighing scale to measure weight of waste produced (discarded warp from the bottom of the beam)

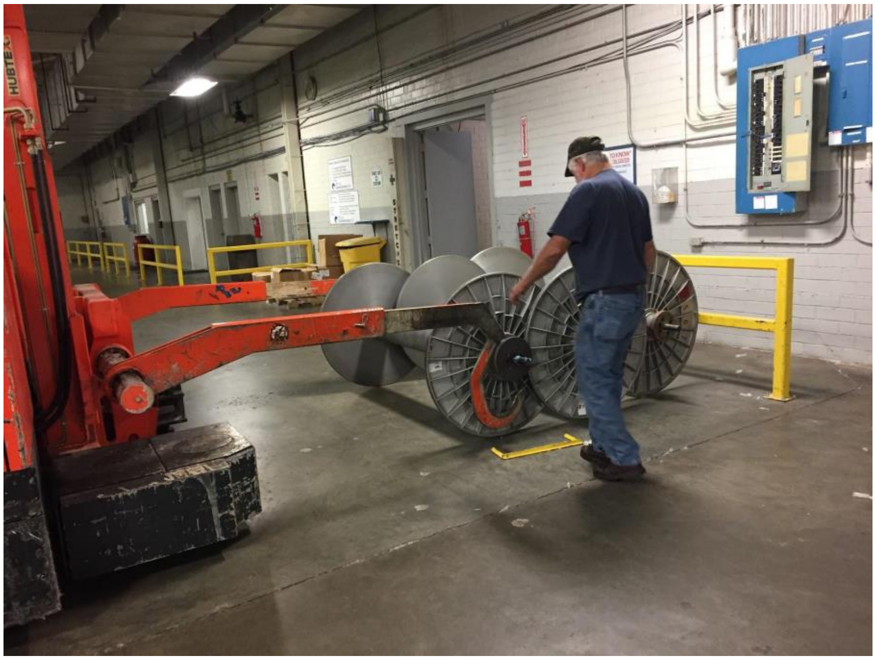

Figure 3.5. Dropping off the depleted beam

Figure 3.6. Installing the new beam

Figure 3.7. Unrolling warp from new beam

Figure 3.8. Placing clamps for knotting

Figure 3.9. Getting the knotting table ready

Figure 3.10. Clamping the new warp sheet onto the knotting table

Figure 3.11. Straightening the new warps yarns by combing

Figure 3.12. Cutting off the extra warp

Figure 3.13. Unrolling and brushing of the depleted warp sheet

Figure 3.14. The tying-in machine being used for knotting

Figure 3.15. Warp unclamped, and tying-in table removed

Figure 3.16. Manual turning of the new warp beam

Figure 3.17. Attaching the collar

Figure 3.18. Tightening the collar

Figure 3.19. Using the handle to wind more warp on the beam to add proper tension

Table 3.1. Beginning, end, and time taken for each task during ground warp tying-in

Task Sequence	Task	Duration (Minutes)	Task Sequence	Task	Duration (Minutes)
1	Removing selvedge yarn tension weights	15	**15**	Clamping the old warp to tying-in table	6
2	Leasing old warp	64	**16**	Replacing lease rod with threads	5
3	Rod insertion at two ends of loom (to hold the master lease up)	12	**17**	Knotting using automatic tying-in machine	35
4	Pulling depleted warp from old beam (waste)	6	**18**	Straightening the knots and warp yarns	3
5	Weighing the waste	4	**19**	Removing tying-in machine & table	5
6	Releasing old beam	10	**20**	Manually rotates the beam to remove slackness	2
7	Installing new beam	5	**21**	Using the handle to wind more warp on the beam to add proper tension	3
8	Unrolling and placing tying-in clamps on new warp	8	**22**	Fabric weaves till knots reach the heddle frames	62
10	Placing the knotting table behind the loom	2	**23**	Brushing knots just before they enter the heddle frame	4
11	Replacing lease thread with lease rods (new warp)	4	**24**	Passing the knots including disengagement of the pile gear, Repair of failed knots*	106
12	Straightening and combing new warp	1	**Total Time = 374 min** * The loom has to run to pass the knots.		
13	Cutting extra length of new warp (waste)	4			
14	Pulling old warp off old beam & brushing it	3			

3.2.2. Non-stop tying-in

Before the new process could be tried out there were two preliminary processes that were vital to the improved process. The first step was to develop a warp sheet accumulator to store the warp tail while the weaving machine is forming the fabric from the main warp sheet. The second requirement to achieve non-stop tying-in was to develop a loom beam winding procedure, at the sizing or warping process, to create a warp beam with tail that will be available for tying-in before warp beam runs out. The warp tail length, which depends on the weaving speed and pick density — or fabric take up speed — must be sufficient to allow time for the tying-in and its associated procedures. The next two sections give a detailed account of how the tail and the accumulator were formed, along with a number of pictures that help in visualizing the process.

3.2.2.1. Accumulator Assembly at P&A

On the 26th and 27th of November 2018, along with the help of one technician from P&A, Mr. Tony Melton from Menzel carried out the task of assembling more than 100 parts to build the accumulator. The process was observed on both the days and a number of pictures and videos were taken to capture and understand the steps of the accumulator's assembly. The accumulator only needed assembling once, and for every other use after it could be easily moved from loom to loom, - The wheels on which it stands and the fact that its body is made of aluminum contribute to its lightweight and easy mobility. Figures 3.20 – 3.32 show the stages in erecting the accumulator.

Figure 3.20. First Side frame of the accumulator

The first step in the process was setting up the first side frame of the accumulator on the ground and then erecting it vertically with the help of a crane and forklifts, shown in the figures below.

Figure 3.21. Erecting the side frame using crane

Once the first side frame was standing vertically, the side bars were attached to it at the bottom location.

Figure 3.22. Attachment of the side bars to the frame

After this the second side frame was assembled on the ground, wheels were attached, and later it was also erected by the help of cranes.

Figure 3.23. Assembly of the second side frame

Figure 3.24. Attachment of the wheel

Figure 3.25. Two side frames erected

Once the two side frames of the accumulator were up and standing, the remaining bars were attached to connect the two faces. This was followed by installation of 2 movable rollers and 7 bottom guide rollers.

Figure 3.26. Attachment of bars that connect the two side frames

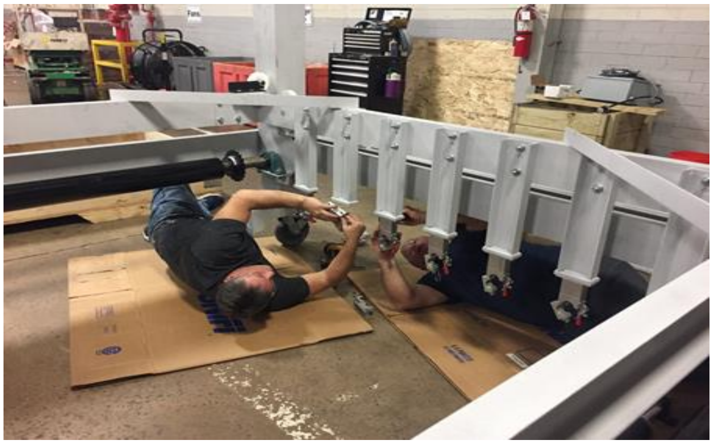

Figure 3.27. Preparation for attaching the guide rollers

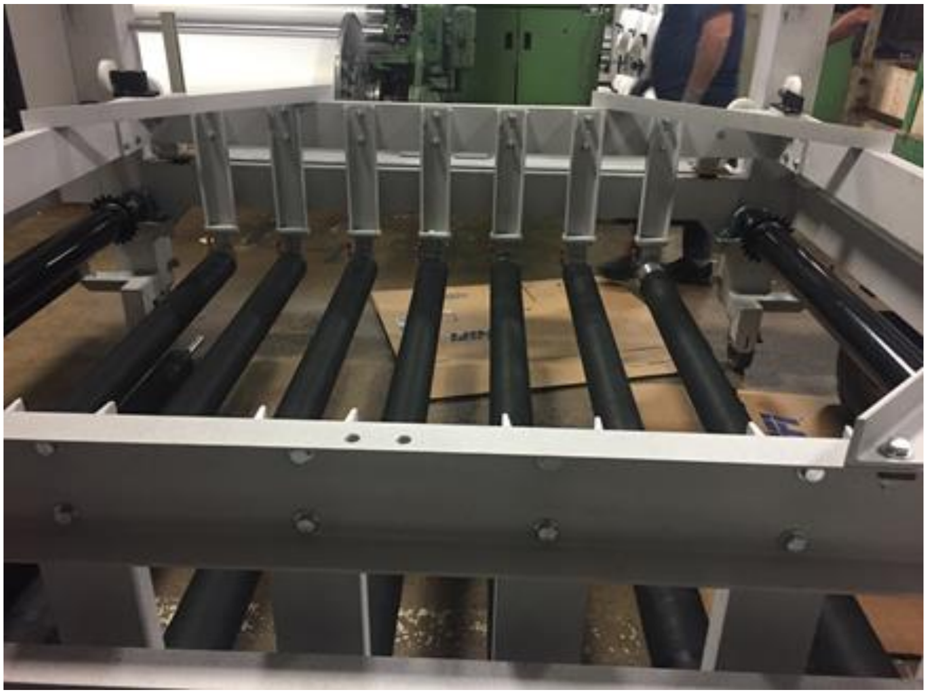

Figure 3.28. Attaching the movable and guide rollers

Following this a number of Chains and gears were attached to the accumulator frame, that would be responsible for giving motion to the rollers and then electrical connections were set up.

Figure 3.29. Fixing the gears and chains that will impart motion

Figure 3.30. Winding chains over gears that were previously installed

Figure 3.31. Setting up the electric connections

The picture in figure 3.32 shows the final look of the accumulator after the whole assembly process was completed.

Figure 3.32. Fully assembled accumulator

3.2.2.2. Formation of warp beam with tail

Loom number 33 at P&A was designated to carry out the first full scale non-stop tying-in trial. The ground warp beam installed on loom 33 had to be specially made for the trial of non-stop tying-in process. This beam was special in the sense that it had to have a tail warp sheet wound at the base layer which would start to show once this beam started to run out. However certain calculations for the length of the warp tail had to be made such that once the tail emerged, the warp beam still had enough warp left on it to continue weaving in the usual manner for as much time as it would take to thread the tail warp through the accumulator and perform tying-in at the back of the loom. The first prototype of a warp beam with tail, which was made at NC State, employed a spring rod hinged between the tail and the main warp shown diagrammatically in figure 3.33 and 3.34. For this prototype the width of the warp beam was 20 inches with 50 ends/inch for a total of 1,000 ends and a yarn count of 42/2. On the other hand, the ground warp beams at P&A are 66 inches wide, with 6480 ends and a yarn count of 150/2 Denier. Because of such a huge size difference the spring rod method for forming the tail beam wouldn't have worked for commercial and wider beams. Hence, an alternative approach to temporarily securing the "tail" to the beam had to be developed. This new approach centered around the use of a flat magnetic strip to hold the tail in place.

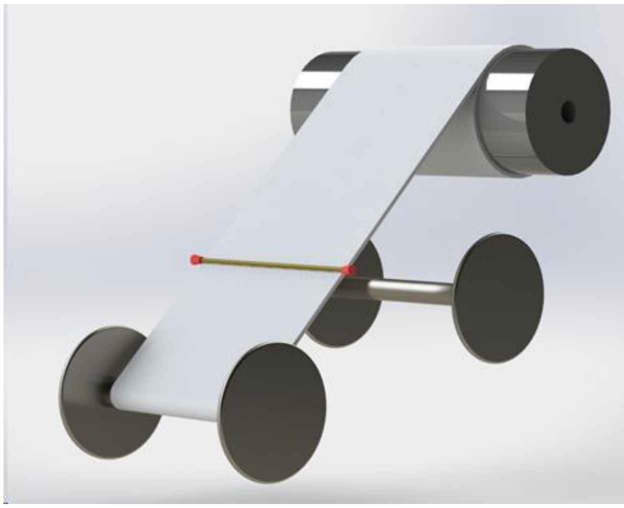

Figure 3.33. Winding warp sheet with feed from tail-beam and Pattern drum

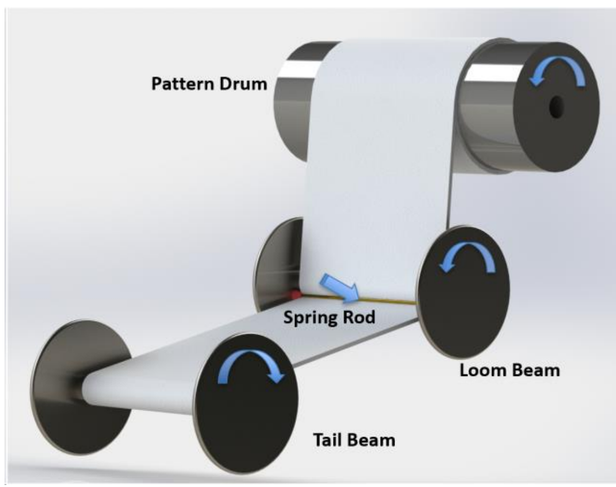

Figure 3.34. Winding warp sheet with feed from tail-beam and Pattern drum

On December 19th, 2018 the first attempt was made by personnel at P&A towards making a production ground warp with a tail. They were able to insert a lease and put 100 yards on a tail beam, and remove it from the collection unit, without much issue. After that they positioned a production beam in the machine in front of the tail beam, with the intention of winding yarn back from the creel and yarn from the tail beam onto the production beam so the tail would come out as the warp neared completion. Unfortunately, the flexible magnetic strip used to try to secure the yarn on the production beam and subsequently running yarn back off the tail beam did not work. It was unable to affix securely to the barrel of the production warp since, the magnetism was not strong enough with yarn sandwiched between the magnetic strip and the beam barrel. To counter this problem, it was believed that the use of some thin neodymium bar magnets glued to a soft rubber strip that spans the width of your beam could be a better solution. The idea being that these magnets are very strong, and the rubber strip adds necessary padding and friction to keep yarn in place.

Magnets were acquired on January 8th, a warp beam with a warp tail was successfully made at P&A using the neodymium bar magnets attached to a thin, steel lease rod which was encased in a fabric sleeve. It was found that the 3" bar magnets needed to be attached to a rigid rod to prevent the magnets collapsing on themselves when trying to put them onto the loom beam. When these longer magnets were attached to the steel lease rod and this whole assembly was placed inside a fabric sleeve, the rigid structure made it easy to work with and it stuck to the beam mandrel really well. Figures 3.35-3.42 are some pictures that were captured to show step by step process of the tail beam formation,

Figure 3.35. Beginning of tail beam

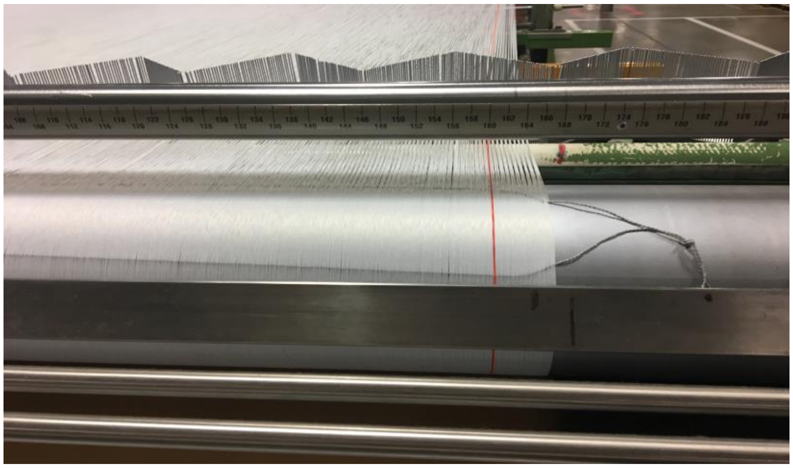

Figure 3.36. Lease being inserted at the end of tail beam

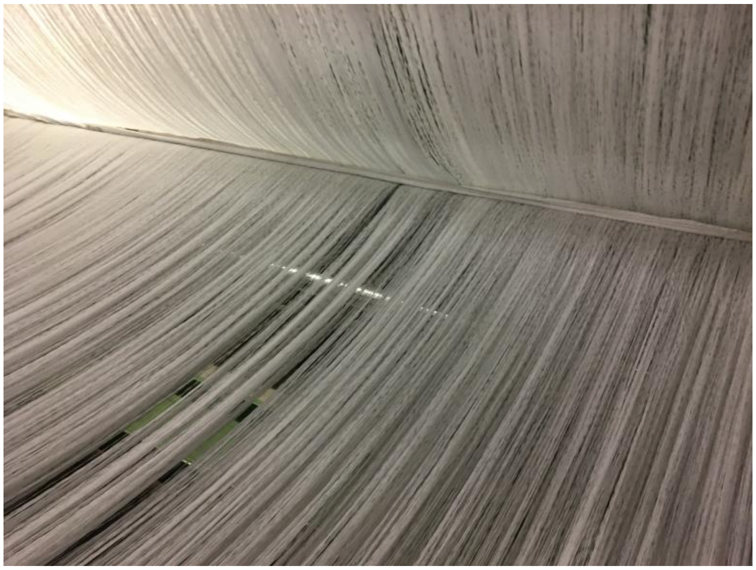

Figure 3.37. Inserting magnetic bar on loom beam

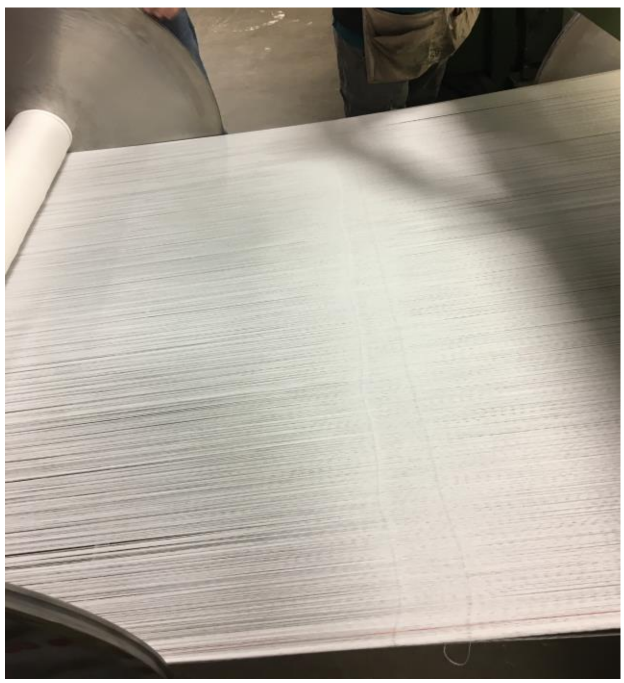

Figure 3.38. Tail beam lease string goes into the loom beam

Figure 3.39. Preparing to tape tail beam sheet

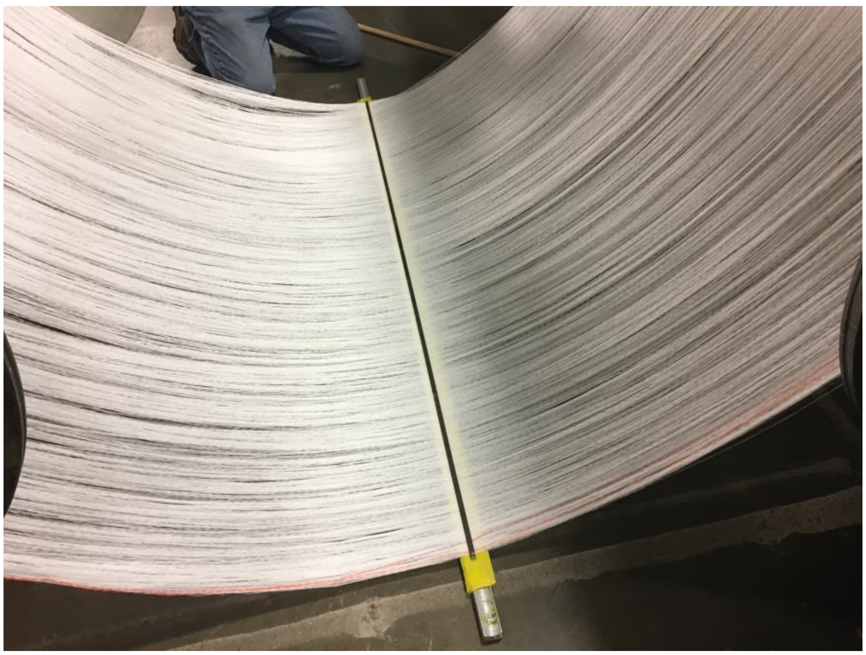

Figure 3.40. Lease rod being put on top of tail beam sheet

Figure 3.41. Second taping of tail sheet

Figure 3.42. Cutting yarn from tail beam

This beam had a 1000 warp yard on it and was installed on loom number 33 on the 12th of January. It was anticipated that 1000 yds of warp would start to run out enough for the tail to show in the next 8 days, however, in practice it took a lot longer than that. The accumulator was positioned in a convenient space behind loom 33 to allow space for the new beam to be placed behind the loom. Finally, on the 4th of February the tail warp showed up.

3.2.2.3. The Non-stop tying-in trial

The first trial for the non-stop tying-on process was conducted on February 7th, 2019. The new and improved process was scheduled to be carried on for the first time at a full-scale level on a loom number 33 (rapier loom) at P&A industrial fabrication LLC in Roxboro. The style of fabric being woven on this loom was Velcover Bond X. The ground warp beam had 6480 warp yarns of 2/150 Denier. The process was observed by a member of the team from NCSU, Menzel and a majority of the staff at P&A.

Once the accumulator was placed in front of loom 33 and the tail warp was threaded through the accumulator a number of issues arose which indicated that the process was not proceeding as intended. These inconsistencies were mostly due to miscommunication within and between the different teams involved in the project. This situation was not a first timer in the history of new product development and is very nicely summarized by this quote: "developing a new product is a complex process involving collaboration across multiple disciplines and a large number of trade-off decisions frequently made without complete information."

Along with identifying some errors in decisions made, the teams also realized the need of making some additional components and attachments to the accumulator, as well as to the process of beaming and threading the tail through the accumulator. All of these additions and alterations needed are summarized below along with a detailed description of what went wrong due to miscommunication or misinterpretation.

3.2.2.3.1. Errors due to miscommunication/misinterpretation:

The first thing that proved to be a big problem was the fact that while creating the warp beam with a tail, the length of the tail was not correctly calculated beforehand and too much yarn was put into the tail which had been wound onto the beam. The accumulator at it maximum setting has the total capacity to carry approximately 50 yards of warp yarn, while the tail was more than 70 yards in length. This made it impossible to accumulate the total tail warp sheet length on the accumulator. Given the fact that on an average P&A looms weave 5 yards of fabric per hour, and that the process of tying-in takes 6 hours (on an average), even 15 yards of warp tail would suffice for the non-stop tying-in process to successfully work, since for the first three hours the loom would continue weaving from the 15 yards of main warp while the tail keeps accumulating, and once the main warp runs out the 15 yards tail can start feeding warp to the loom as the accumulator decumulates, all the while tying-in is being performed.

The second error made was accumulating the tail in the accumulator first hand even before tying-in started. The idea of the non-stop process is to take the tail warp straight through the bottom of the accumulator and clamp it to the tying-in table (where the new warp sheet is already clamped). subsequently once tying-in begins and the loom keeps weaving, the tail keeps emerging out, and the movable rollers of the accumulator are supposed to travel upwards thereby accumulating the tail. Thus, by already accumulating the tail even if it had the correct length would not have helped save time and run the process smoothly.

The third error was once the tying-in was completed, the accumulated tail warp was wound onto the newly installed beam, instead of feeding it to the loom from the accumulator. This act of winding the tail onto the beam resulted in a warp beam with less that optimum tension in the yarns for weaving (figure 3.43). This led to waste of almost 70 yards of yarn.

Figure 3.43. Loose Ends on New Loom Beam

3.2.2.3.2. Additional parts and changes needed

1. Due to the strong magnets employed some of the warp yarns clung onto the beam mandrel, thereby experiencing damage. Figure 3.44 shows this as the warp sheet is coming off the beam just before the magnets are removed. Thus, the next time there would be a need to protect the yarn from the mandrel by wrapping mandrel with Kraft paper first.

Figure 3.44. Warp Sheet Before Magnet Bar Removed

2. Once the tail warp emerged the team experienced difficulty in handling 6480 loose warp ends and threading them through the accumulator. To counter this problem, the addition of a taped lease bar to the end of the tail, in order to keep the warp sheet open, was suggested. This could be done by using a very sticky tape like Gorilla Tape that would be applied on both sides of the warp sheet.

3. While the tail beam was formed at P&A a crane was used to lift the tail beam in air, all the while and before the tail was transferred onto the production beam. It may not always be that a crane is available for this process and thus another suggestion was to develop a beam lift that would raise the tail beam off of the floor when it is removed from the winder so that an empty warp beam can slide underneath the tail warp sheet.

Figure 3.45. Crane being used to lift the tail beam

4. As mentioned earlier the looms at P&A have the capacity to carry four warp beams at a time (2 ground and 2 pile), and they usually weave with just three of these positions filled. Thus, the fourth bearing for an additional ground beam was a fortunate thing for P&A and this process. While the old warp was nearing completion and the tail was beginning to show, the ground beam was moved up from the bottom ground bearing to the top ground warp bearing. This allowed P&A to install a new warp beam in the now vacant bottom warp beam bearing. However, a procedure should be developed for modifying the backing beam let offs, which can allow for more easy changing of the beam running position from the top to the bottom position.

Figure 3.46. The old warp beam moved up to the middle bearing

5. Another attachment that can help make the process smoother is a handle/hook that can be used to pull the tail as it comes off the backing beam through the accumulator. This could be a simple cable winder where the warp clamp is attached to cable to be gently pulled through the accumulator.
6. One of the major attachments needed is the presence of a clamp that can be added on the exit end of the accumulator. This clamp should be able to clamp the tail warp sheet to the body of the accumulator while tying-in is being done. This is necessary because if the tail is not clamped and the movable rollers on the accumulator start moving upwards (for accumulating the tail) the force exerted on the tail warp sheet would pull the tying-in table up from the ground and into the accumulator.
7. An additional turning roll needs to be added towards the exit end of the accumulator to separate the new warp sheet and the tail warp sheet before going into the tie in machine

Figure 3.47. The tail warp and new warp sheet in contact

8. It is needed to provide back tension to the tied in warp sheet as it is being consumed by the loom. There isn't enough tension on the warp to enable the loom to run and it was discussed that a possible solution might be to have the last roll at the exit end of the accumulator be

mounted such that it could run down a parallel set of slides that would provide tension to the warp sheet. Additionally, this roll has to end up in a high enough position so that the new warp sheet does not rub against the yarn on the new beam. In other words, the angle between the whip roll and the yarn on the beam has to be great enough for clearance of the new warp sheet.

In the future as the collaboration between the teams from NCSU, P&A and Menzel continues designs for all the above-mentioned enhancements for the process would be finalized and brought to life. Once ready another full-scale trial would be conducted for the Non-stop tying-in process. As suspected initially by the inventors such a situation of iterations was completely expected in this case of disruptive improvements in a process that has been done in the same way since years. This situation also instilled in the team the motivation to embrace iterations as a process of improvement. At the end of the day the goal of building something is to build something and not to not make mistakes.

CHAPTER 4: TENSION

4.1. Introduction

Tension is one of the most important criteria for the processing of any textile material, especially after the spinning stage. During weaving, tension plays a pivotal role in fabric formation and generating the right properties for the fabric, along with imparting the desired weaving efficiency. Thus, the yarns present on the loom during weaving are more affected by tension than the fabric or the fiber. Only when these yarns are held under correct and optimum tensions is it possible to properly interlace warp and weft to create fabric (Neogi, 2015).

The effect produced when two forces pull against each other is termed as ‘Tension’. Therefore, tension is a uniaxial force that causes either the extension of a body or the balancing force inside a body resisting extension. In other words, tension on a yarn is the tensile force that develops within it when it is given an external tensile strain, hence, the amount of external strain on a yarn determines the magnitude of yarn tension. The units used for measuring tension are Grams Force and centinewton (cN) (Neogi, 2015).

4.1.1. Tension during weaving

Yarn tension plays the most important function in weaving among all the different processing stages involved from spinning to weaving. For creation of a clear shed and smooth insertion of the weft and thus proper weaving operation, correct yarn tension is essential. Optimum warp tension is also required to hold the fell of the cloth in the most correct predetermined position for getting the required pick spacing. In addition to warp tension, tension in the weft yarn is also important since it helps in removing slackness in the yarn during insertion and ensured that the desired length of the pick is inserted into the shed. Since warp and weft yarns are interlaced during weaving, tension is also a parameter that determines the crimp generated in these two sets of yarns and crimp is what governs a number of fabric properties (Neogi, 2015).

For best results it is desired to keep the yarn tension levels as uniform as possible throughout the process. This is so because high variation in tension levels can strain the yarns and even cause damage to the machinery, which will in turn result in loss of production and degraded quality of the end product (Neogi, 2015).

4.1.2. General form of warp tension variation

When the warp shed is formed during weaving it causes the warp yarns to move up and down and thus leads them to experience varying magnitude of tension. In addition, during Beat-up there is a sudden rise in the tension experienced by the warp yarns. These primary weaving functions thus result in variations of the tension values from their preset values. Thus, because of shedding and beating a cyclic tension variation exists, however the let-off and take up motions are intended to maintain a constant mean tension (Neogi, 2015).

In figure 4.1, warp tension variation for a plain weave fabric as a result of beat-up and shedding can be clearly seen. The sudden rise in tension due to the beat-up force can be seen at point C, while the variation in tension due to shed formation can be seen from E to F, which is still high in magnitude but for a longer time due to shed dwell. The time when all the yarns are at the same level due to shed change, the lowest tension is observed, represented by point A in the figure. Since the method adopted for tension measurement indicates the overall tension of the entire warp sheet, the warp tension varies in exactly similar manner in successive picks (Neogi, 2015).

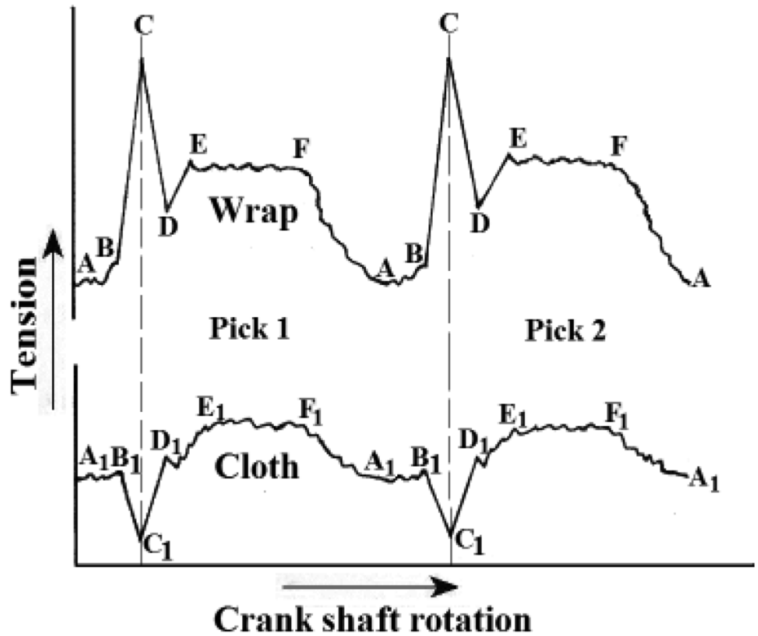

Figure 4.1. Warp tension variation for a plain weave fabric (Neogi, 2016)

It is a well-known fact that as the amount of warp on the warp beam keeps diminishing, the warp tension goes on increasing unless the dead weights on the loom are changed. Figure 4.2 shows a diagram of the warp beam and the forces that act on it. The relation that warp tension increases as the warp diameter decreases can be proven by a simple torque balance equation of forces acting on the beam. Torque balance equation around the center:

$R_{hub}*W=R_{warp}*T$

$T= R_{hub}*W/R_{warp}$

since, $R_{hub}*W$ is constant at P&A (because they don't change the weights at any time) and R_{warp} keeps on decreasing as the loom keeps weaving, it is clear that with decreasing warp radius the warp tension will keep on increasing.

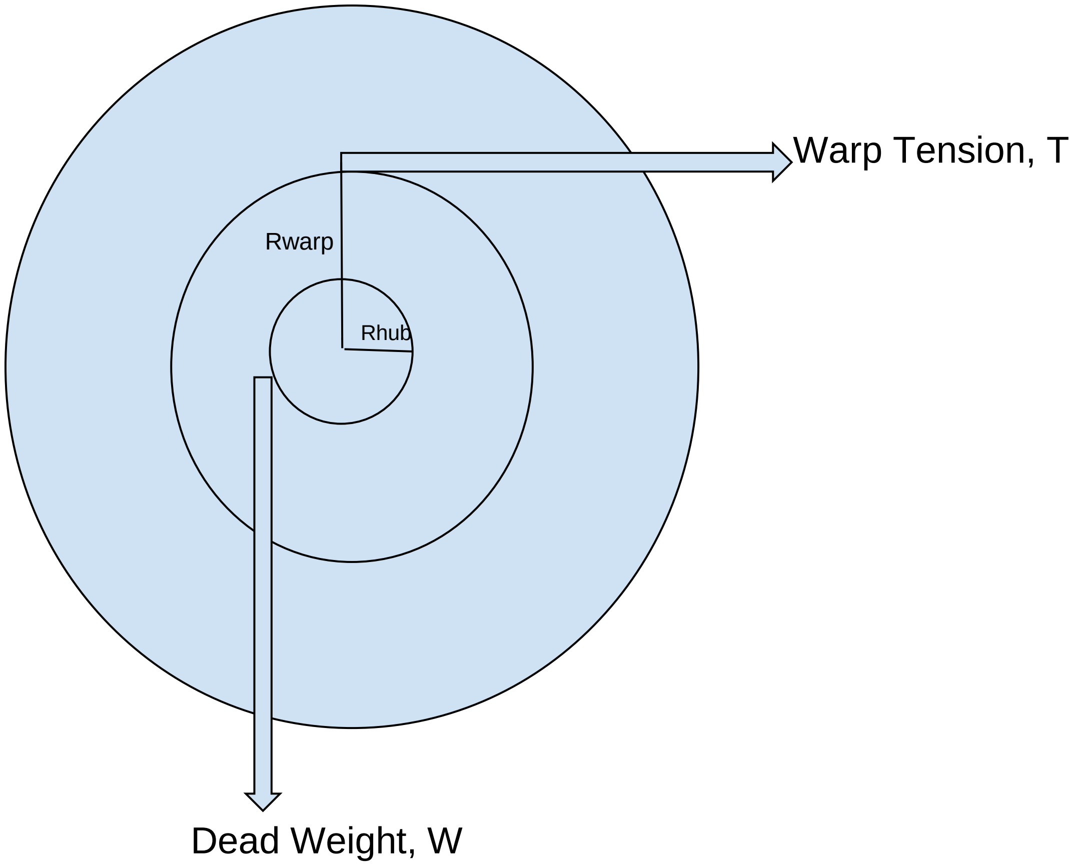

Figure 4.2. Forces acting on the warp beam

In an investigate of the effect of fabric structural parameters and weaving conditions to warp tension of aramid fabrics for protective garments, it was found that the measured mean warp tension increases with an increasing weave density coefficient. High warp tension variation during weaving was observed at the low and/or high fabric cover factors due to the high stiffness and low extensibility of the aramid filament (Kim, S. J., & Kim, H. A., 2018). In another study researchers established that warp tension is the highest at the middle and decreases gradually towards the two sides of the warp sheet. The reason of this variation is not very clear but it is assumed that this is due to the fact that the weft is free to be pulled into the fabric during beat-up of the weft as a result the warp yarns near the selvedge are less likely to produce as much crimp as is produced by the center (Md Mahbubul, 1997). An increase in weft density decreases the warp tension variation over the loom width. Warp tension variation over the loom width increases with an increase in total average warp tension level. An increase in weft yarn thickness decreases warp tension variation over the loom width which means that warp tension varies less over the loom width as weft yarn becomes thicker (G. Ozkan, 2010).

4.2. Preliminary tension measurements during conventional weaving

Tension measurement in the warp yarn was a big requirement for the successful completion of this process. This was important because when the warp is on the loom, the tension in the warp yarns is controlled by the weights hanging on the loom as well as by the take up and let off motions. However, while using the non-stop tying-in process, the warp is given tension by adding weights on the accumulator and it was of utmost importance that this imparted tension was in the same range as the tension of the warp on the loom. If there was a discrepancy in the tension values the fabric formed would not have optimum properties and might even have defects in construction.

Tension measurements were taken by using the ETMX - ETMPX Data Logging Digital Tension Meter. This device consists of three long, closely spaced slender shafts with precision guide rollers or pins at their ends combine with the latest in microprocessor technology. The ETMX models feature miniature, high speed rollers for yarn speeds up to 2000 m/min. It has an accuracy of ±1 % full scale ±1 digit or better (typical ±0.5 % full scale).

P&A has airjet looms that have been manufactured by Van de Wiele, which is a Belgian Textile Machinery making company. The looms range in date of manufacture, the oldest were made in the 1960s, and the newest in the 1990s. All of these looms have the capacity to run four warp beams at a time, two backing beams and two pile beams. Usually at P&A these looms are run with three beams (one backing and two pile), however sometimes they do run at full capacity of all four warp beams. In this study the backing warp beam is addressed as ground warp beam and the two pile warp beams are addressed as pile 1 and pile 2.

The first phase of tension measurements was done in early July of 2018. Tension was measured for a group of consecutive ground warp yarns that were randomly selected as a bunch. Because of this random selection in the number of yarns through which readings were taken, the data obtained was not fit for use and was hence discarded. It was decided that in subsequent visits tension would be recorded for either a single yarn or a group of four yarns.

For the second phase of measurements (August 2018), tension was recorded for a single ground warp yarns as well as single pile 1 and pile 2 warp yarns. The tension measurements for single ground warp yarn were carried out on at 6 looms, each of which had different styles of fabrics on them with varying pile heights, while tension for single pile warp yarns was recorded at 3 different looms. The ground beams on each loom had a total of 6480 warp yarns and all of these yarn were polyester filament yarns with 2-ply, each ply 150 denier, or a total count of 300D. Both pile 1 and pile 2 beams had 504 ends each, these yarns were either polyester or acrylic ring spun, and their counts varied from loom to loom.

The measurements on each loom were carried out at five different locations along the width of the warp beam and were taken for a minute at the rate of 100 samples/second. All the readings were recorded in Gram Force and the data obtained was recorded on a laptop in Excel format in two different sheets, one for the ground warp yarns and one for the pile. Table 4.1 tabulates the readings obtained for tension on single ground warp yarns at six different looms and table 4.2 tabulates the same for single pile warp yarns at three different looms. The tensions presented in both these tables was found by taking an average of the average tension value recorded at five positions across the width of the warp beam for all the looms. The tables also include some general specifications affiliated with each loom viz. loom speed, picks per pinch, style of fabric being produced and pile height.

Table 4.1. Preliminary tension measurements obtained for a single ground warp yarn

Loom No.	Fabric Style	Picks per inch	Loom Speed (PPM)	Pile height (mm)	Average tension for single ground beam yarn, gf
1	Maxicover	48	182	39	92.11
3	DURABOND39, 0000, GRIEGE	48	176	39	99.518
29	PB410-50	50	167	29	97.74
41	WOOSTVELBF 2,0000, GREIGE	50	128	31	56.392
135	Durabond 39, 0000, GRIEGE	48	182	39	78.27
136	Maxicoverbond, 0000, GREIGE	48	148	39	84.838

Table 4.2. Preliminary tension measurements obtained for a single pile warp yarn

Loom No.	Fabric Style	Picks per inch	Loom Speed (PPM)	Pile height (mm)	Average tension for single pile 1yarn, gf	Average tension for single pile 2 yarn, gf
41	G,WOOST VELBF,2	50	128	31	20.63	16.02
29	PB410-50	50	167	29	11.63	8.71
1	G, Maxicover	48	182	39	35.21	Missing
Total Number of Pile yarns- 504						

In the third phase of measurements (October 2018) tension was measured on a group of 4 consecutive ground warp yarns. From these measured values for 4 warp yarns, the average tension in one warp yarn was calculated, sets of both these values are shown in Table 4.3. This value was then compared with the value obtained while measuring tension for single warp yarns in phase two of the preliminary trials, which is shown in table 4.4

Table 4.3. Average tension obtained for four ground yarn, and calculated value for single ground warp yarn

Loom No.	Fabric style	Loom Speed (PPM)	Average tension obtained for four ground yarn, gf	Tension calculated for single ground warp yarn, gf
26	Polybond 410-44	146	384.056	96.014
41	G, WOOSTVELBF2, 0000, GREIGE	128	254.958	63.7395
8	G, POLYBOND 410-44 ,0000, GREIGE	146	376.914	94.2285
136	G, Maxicoverbond, 0000, GREIGE	148	269.712	67.428
3	G, DURABOND39, 0000, GRIEGE	176	389.684	97.421
1	G Maxicover	182	346.606	86.6515

Table 4.4. Comparison of tension calculated for one warp yarn (using tension obtained for 4 yarns, from table 4.3) and tension measured for single ground warp yarn (from table 4.1)

Loom no.	Tension calculated for single ground yarn, gf	Tension measured for single ground yarn, gf
41	63.7395	56.392
136	67.428	84.838
3	97.421	99.518
1	86.6515	92.11

4.2.1. Preliminary Data Analysis

Because of the type of fabric being produced, coupled with the significant amount of post loom finishing, it was evident that P&A as a company does not give much importance to tension variations in their looms and this was evidenced in the data obtained. There was a variation in the tension values from loom to loom and even between yarn to yarn and position to position on the same loom. Charts were plotted from the data and represented as tension vs time. However no strict trend was observed in the plots, although an irregular cyclic trend did exist over all. As an example, a plot made for a single ground yarn on loom 41 can be seen in figure 4.3. This plot is for tension(grams) against time(seconds). This plot is one out of many examples of an irregular tension cycle that varies in magnitude with time for a given warp yarn. The sudden high peak and the gradual trough that can be seen in figure 4.3 is an example of a variation in the recorded values due to the device being handheld. In the secondary tension measurements this cause of variation was removed by building a stand for the tension meter and more information about it is addressed in section 4.3.

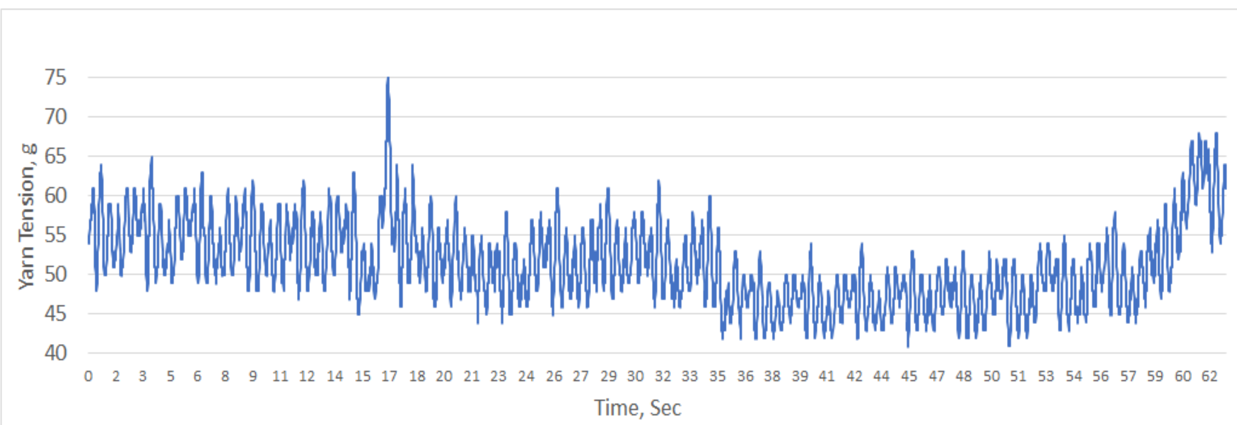

Figure 4.3. Plot between tension for a single ground yarn vs. time for loom #41

Similar to figure 4.3, figure 4.4 is also a plot between time and tension for a single ground yarn on the same loom (#41), this graph was plotted by taking only the first 1500 data points out of the total 6000 recorded. The cyclic trend in this plot is more constant in magnitude and can be clearly observed. The number of peaks in figure 4.4 can be roughly counted to 32 in this plot for 15 seconds. The orange dots indicate picks that were inserted into the loom during the duration of these 15 seconds. Considering one peak occurs every time a pick is beaten to the fell of the cloth (since the orange dots roughly are in sync with the peaks in the plot) for 60 seconds we would have 128 peaks, which is the same as loom# 41's reported loom speed of 128 Picks/min.

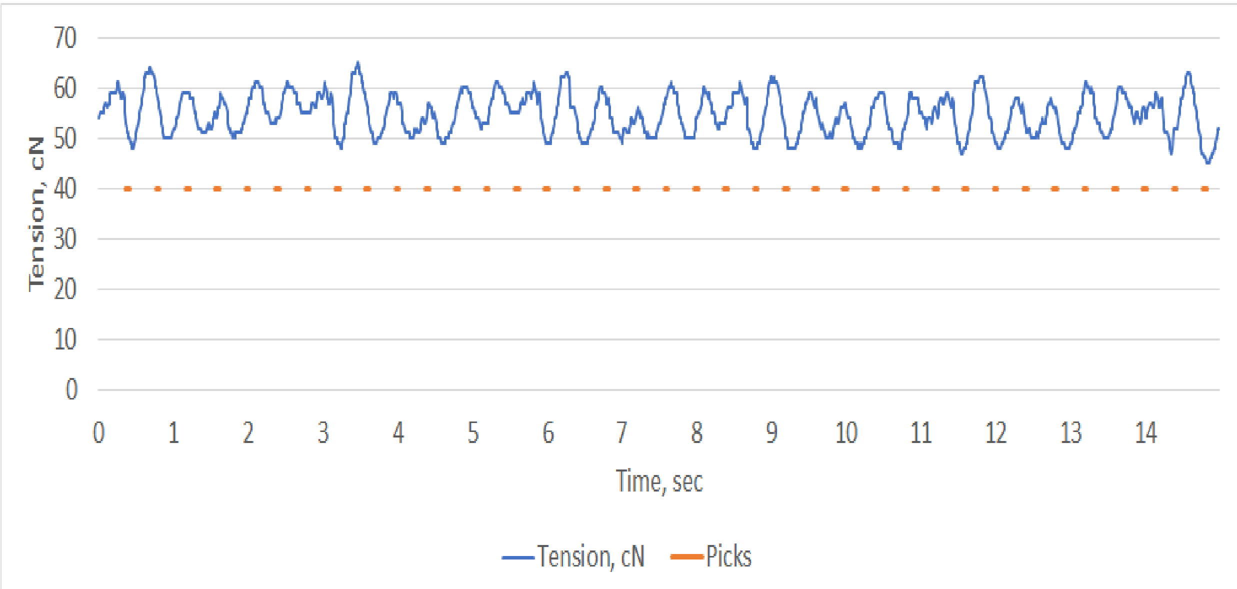

Figure 4.4. Plot between tension for a single ground yarn and time for loom #41

Figure 4.5 is also a plot between tension (grams) and time(seconds) taken over the duration of one minute on a single ground yarn of loom 26. This is yet another example of very many inconsistency in the magnitude of tension along with sudden peaks and dips.

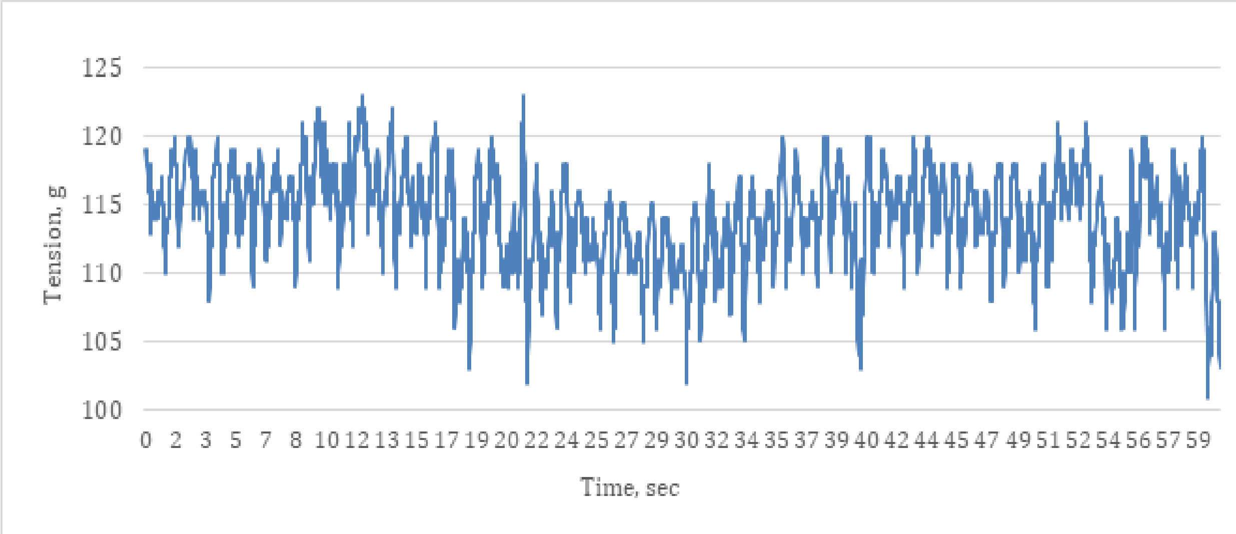

Figure 4.5. Plot between tension for a single ground yarn and time for loom #26

The graph in figure 4.6 is the plot between time in seconds and tension for a group of 4 ground yarns on loom number 1. This graph was plotted by taking 2000 data points out of the 6000 recorded. This plot depicts tension for 4 yarns held together, and this fact is clearly evidenced by the magnitude of tension being in the range of 390-440 g.

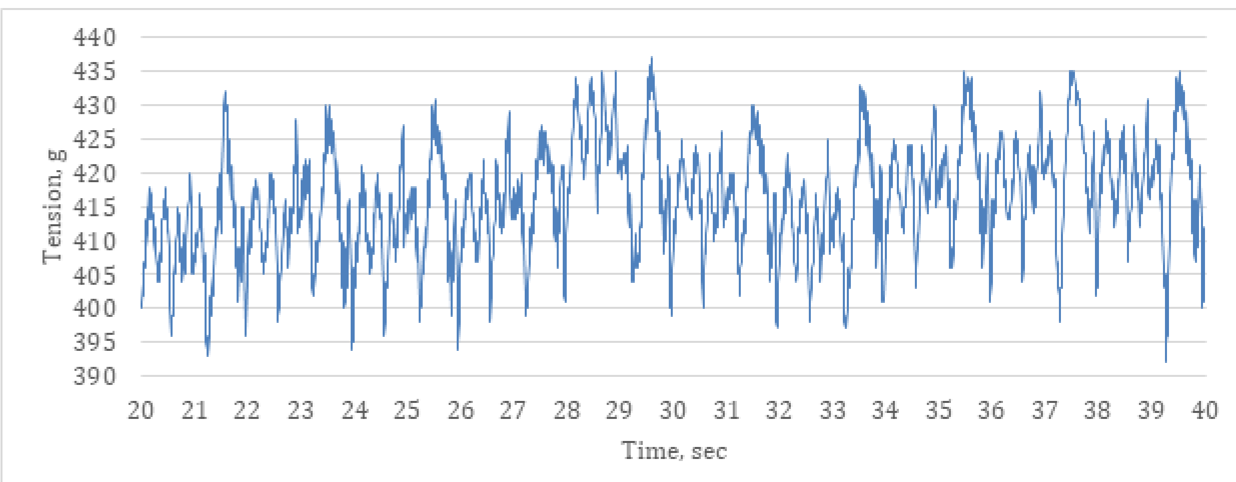

Figure 4.6. Plot between tension for a group of 4 ground yarns and time for loom #1

4.3. Tension measurement during conventional weaving

Since analysis of the preliminary tension measurements yielded a number of inconsistencies in the data recorded, it was decided to remove one of the main factors that may have been responsible for the high variations. In the preliminary method the device was held in hand while a yarn passed through its metal pin, all the while the loom was running and that may have resulted in movement of the hand which held the device as well. This factor of variation was removed by building a stand that could hold the tension meter. This stand was built by Mr. Tri Vu, Specialty Trade Technician at Wilson College of Textiles. The stand was in the shape of an inverted L and stood on four legs. The arm attached to the vertical metal rod, had an envelope at the end wherein the tension device could be clamped. The height of the stand, as well as the length of the arm could be adjusted according to the capacity of the warp beam. Figure 4.7 shows a picture of the whole set up at loom#11 at P&A.

Figure 4.7. Setup of the Tension device clamped onto the stand

In this fourth phase of data collection, there was an attempt at removing another factor that might have caused variations in the data. For this trial the five positions across the width of the warp beam where tension was recorded were pre measured, these points were spaced equally across the beam. The warp beam width recorded was 66 inches and thus, the leftmost position for recording tension was taken to be 1 inch (P1), followed by 17 inch (P2), 33 inch (P3), 49 inch (P4) and 65 inch (P5). Figure 4.8 and 4.9 show tension being measured at P2 and P3 respectively.

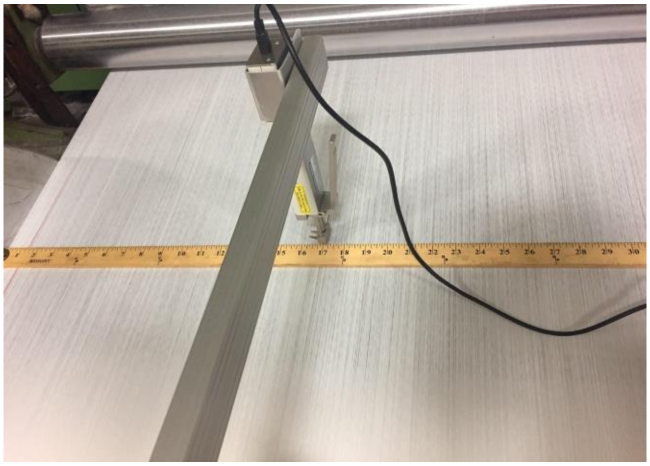

Figure 4.8. Tension being measured at 17 inches from the left flange or at Position 2

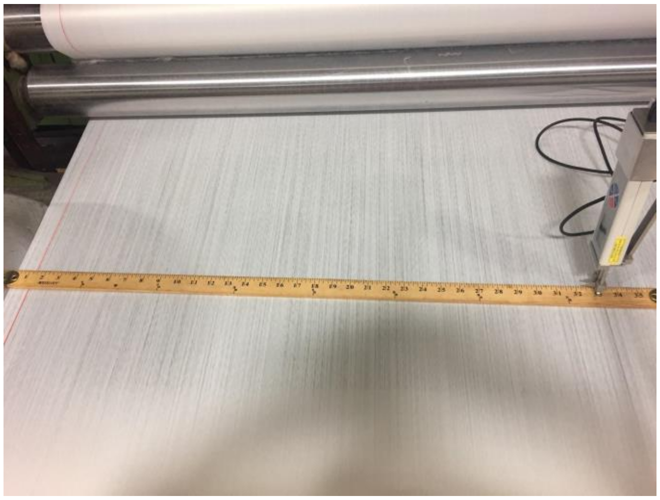

Figure 4.9. Tension being measured at 33 inches from the left flange or at Position 3

In the fourth phase of trials for tension measurements, the capacity of the warp beam was also taken note of. As indicated earlier, it is a known fact that as the warp beam capacity keeps decreasing, if no change in dead weights mounted on the loom is made, then, the warp tension keeps increasing. Thus, it was important that the warp beam capacity on each beam was recorded. The beam capacity was measured by the use of an inch scale that was placed vertically just on top of the warp beam and touching the beam's flange. The distance from the top of the warp to the flange circumference was recorded. This distance when subtracted from the radius of the warp beam gave a direct measure for how full or empty a warp beam was. Figure 4.10 shows the measurements being taken to determine warp radius.

Figure 4.10. Measuring the distance from the warp on the beam to the edge of the flange

After applying all these measures for removing systematic variability in tension magnitude, the fourth-round tension measurement was conducted, and the data was recorded in an excel spreadsheet. It was observed that for two looms out of the four at which tension was recorded, the tension values considerably dipped in magnitude at position 1 and 5, which were at 1 inch and 65 inch respectively from left to right across the warp beams width. This sharp dip in magnitude could have only been possible because of that particular yarn at which tension was measured either being a slack end or because it was too close to the selvedge. Table 4.5 shows the tension values measured at all the five positions for loom number 23 and 5. The sharp dip in magnitude can be seen at position 1 for both the looms.

Table 4.5. Tension recorded at five positions for a single ground yarn at loom# 23 and 5

Loom no.	Positions				
	1	2	3	4	5
23	8.08	31.43	26.36	73.16	60.37
5	4.41	47.42	45.64	39.92	26.25

Table 4.6. Secondary tension measurements for single ground warp yarns

Loom No.	Fabric Style	Picks per inch	Loom Speed (PPM)	Pile height (mm)	Radius of warp sheet, inch	Average tension for single ground beam yarn, cN
11	Velcoverbond	48	147	31	12.9	80.502
23	PB260-50	50	175	20	13	39.88
22	PB410-50	50	149	31	5	90.356
5	Velcoverbond/Durabond6	48	182	43	3.5	32.728

Because there was a possibility that some of these results were outliers it was decided to repeat the measurements but to avoid taking readings in regions near the selvedges. Thus, for the fifth round of trials for tension measurements it was decided to measure the five positions across the warp beam width excluding at least 3 inches from both sides. The average values of tension obtained in this phase of secondary measurement for single ground warp yarns measured at four different looms are concisely tabulated in table 4.6.

In this fifth phase of measurements the positions across the warp beam's width were altered a little to remove variations caused by slack/selvedge ends as discussed above. This time the readings were taken at 5, 15, 25, 35, 45, 55, & 65 inches from left to right of the warp beam and are presented in table 4.7. The average tension for whole warp sheet was calculated by multiplying average tension for single yarn by 6480 (total number of warp yarns) for each loom.

Table 4.7. Secondary tension measurement for single ground warp yarns

Loom no.	Loom speed, ppm	Radius of warp, inch	Avg. tension for a single warp yarn, cN	Average tension for warp sheet, kN
11	147	12.8	114.46	7.42
23	175	13	110.1	7.13
5	182	16.9	71.19	4.61
9	129	11.2	109.8	7.22

Despite using a tension stand and eliminating the possibility of variation in values from slack ends in the selvedge the overall tension values obtained in the secondary trial were also not the most consistent. The variations from loom to loom and position to position within a loom still existed (table 4.8). However, for any particular reading the cyclic trend observed after plotting the data was much more consistent than in the preliminary trials, there were no more sudden dips or peaks in the plots and a clear tension cycle coinciding with the weaving cycle could be seen, an example is shown as figure 4.11. The 25 orange dots indicate each pick inserted into the loom warp shed in those ten seconds.

Table 4.8. Shows existing variability from position to position and loom to loom

Loom no.	Average tension, cN	Tension (cN)						
		Positions (inch)						
		5	15	25	35	45	55	60
11	114.6	128.31	116.25	124.41	116.37	106.37	104.32	105.09
23	110.1	96.44	122.36	122.77	109.11	112.45	103.93	103.64
5	71.9	missing	55.83	84.5	51.23	108.9	55.5	missing
9	11.40	114.12	116.58	114.9	107.28	107.13	109.97	109.8

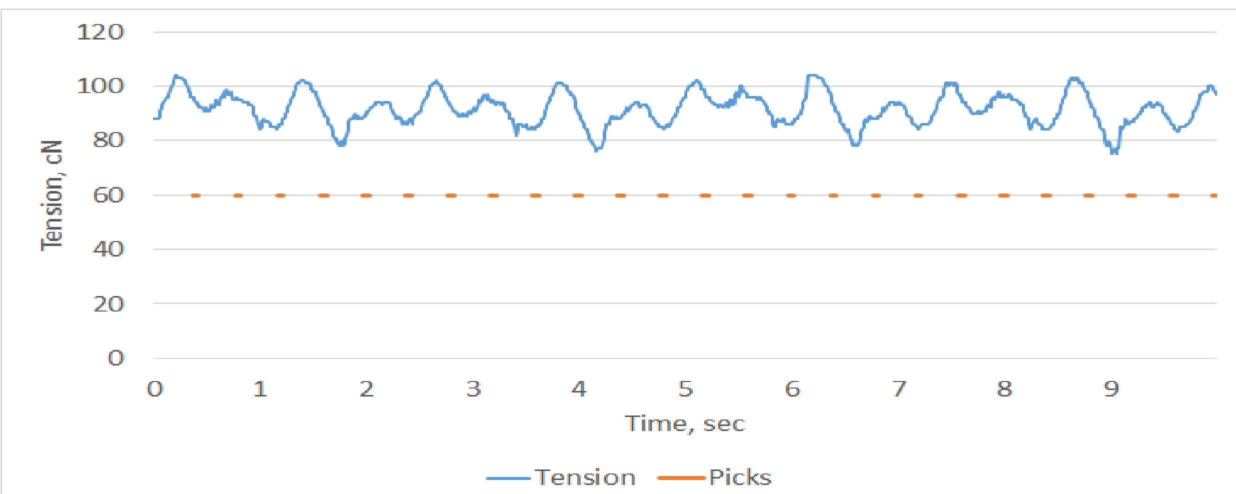

Figure 4.11. More consistent cycles of tension after a stand was employed for holding the tension meter

In the sixth phase of measurements tension was recorded on singular warp yarns during the warping process. The readings are tabulated in table 4.9. The idea was to get an estimation of how much tension is imparted to the warp yarn during warping and compare it to the tension recorded at the warp yarns on the beams during weaving. The comparison gives an idea of how much tension is already in the warp yarns from the warping process and how much is being imparted to them from the loom let-off or take up mechanisms and the weights hanging on the side of the looms.

The section warp beam being prepared had 504 warp ends and was one of the 12 section beams which would later be put together on the collection warper to prepare the weaver's beam. The tension measurements were taken at four positions namely at the back of creel (A), front of creel (B), between creel and guide plate (C), between guide plate and beamer (D). These positions are marked in figure 4.12 and then shown individually in figure 4.13, 4.14 and 4.15 respectively.

Figure 4.12. Positions where tension was measured during warping

Figure 4.13. Individualized depiction of position A

Figure 4.14. Individualized depiction of position C

Figure 4.15. Individualized depiction of position D

Table 4.9. Tension in single warp yarn during warping

Position	Average Tension, cN	CV%
Back of creel	31.86	4.991
Front of creel	40.03	2.837
Between creel and guide plate	42.33	2.906
Between collection point and beamer	51.65	4.240

4.3.1. Data analysis

The tension readings obtained for loom number# 22 were plotted against time (10 seconds), figures 4.16- 4.20 are plots drawn for tension recorded on single ground yarns at each of the five positions for this loom. As can be observed from these plots the tension values obtained after using the stand for clamping the tension meter gives much more consistent and cyclic plots. The orange dots in the plots represent each pick inserted into the loom in the ten seconds for which the graphs are plotted. The lines in figure 4.16 (b) were added to get a clearer picture of a peak occurring in the tension magnitude every time a pick was inserted. However, the lines do no coincide with peaks, which is logical because it can’t be known if insertion of picks coincided with the timing of the beginning of the tension measurement. The tension magnitude ranges from 60-110 cN, averaging at 90.356 cN and a total of 585.81kN for the whole warp sheet.

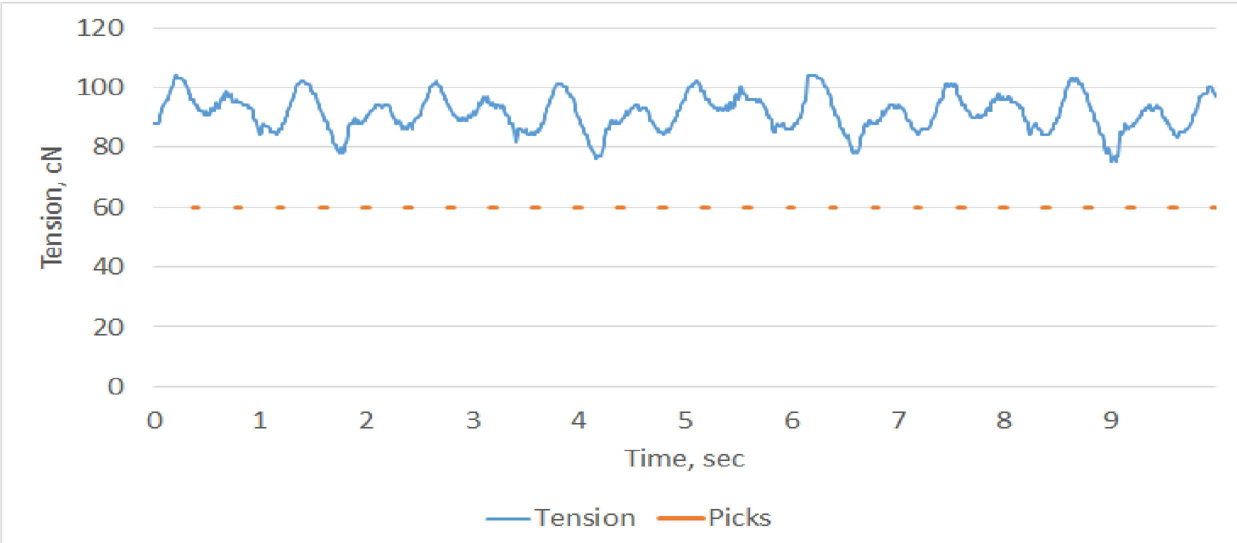

Figure 4.16 (a). Plot between Tension (cN) and time (sec) for loom #22 at position 1

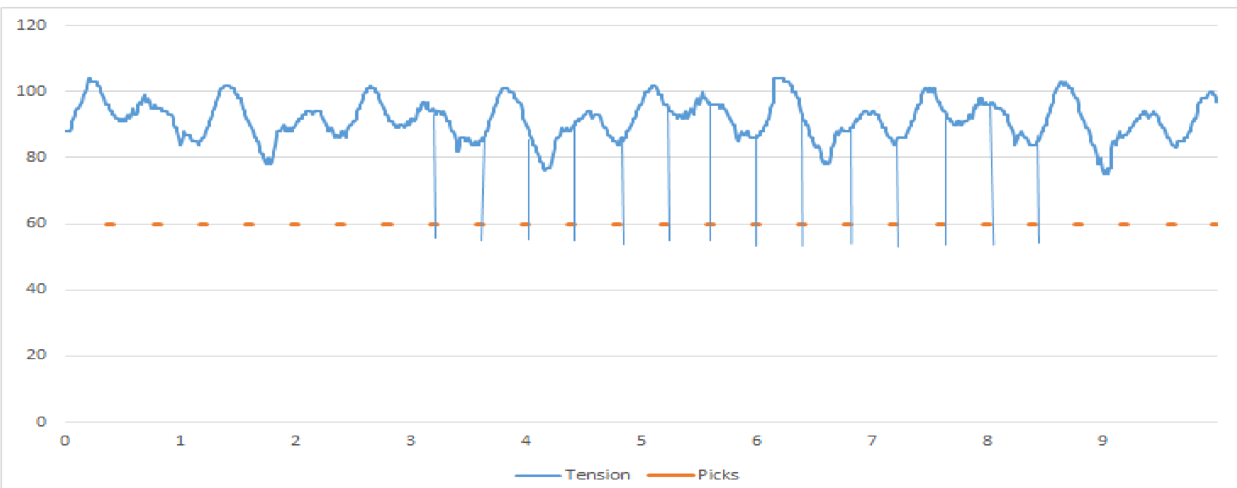

Figure 4.17 (b). Plot between Tension (cN) and time (sec) for loom #22 at position 1

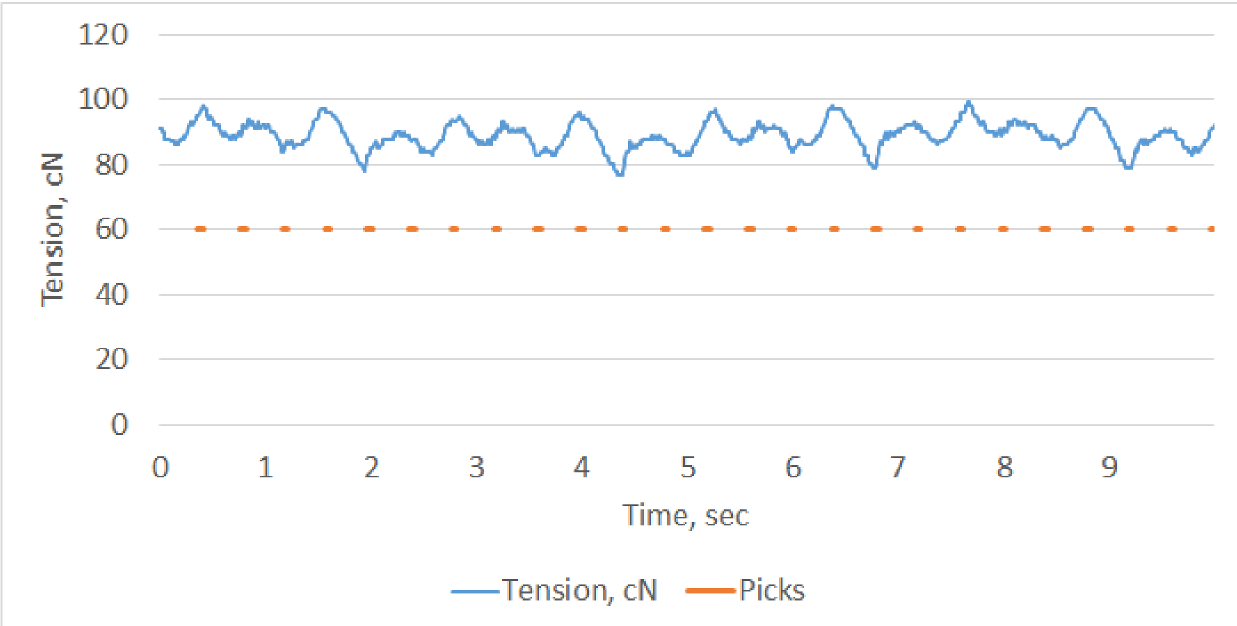

Figure 4.18. Plot between Tension (cN) and time (sec) for loom #22 at position 2

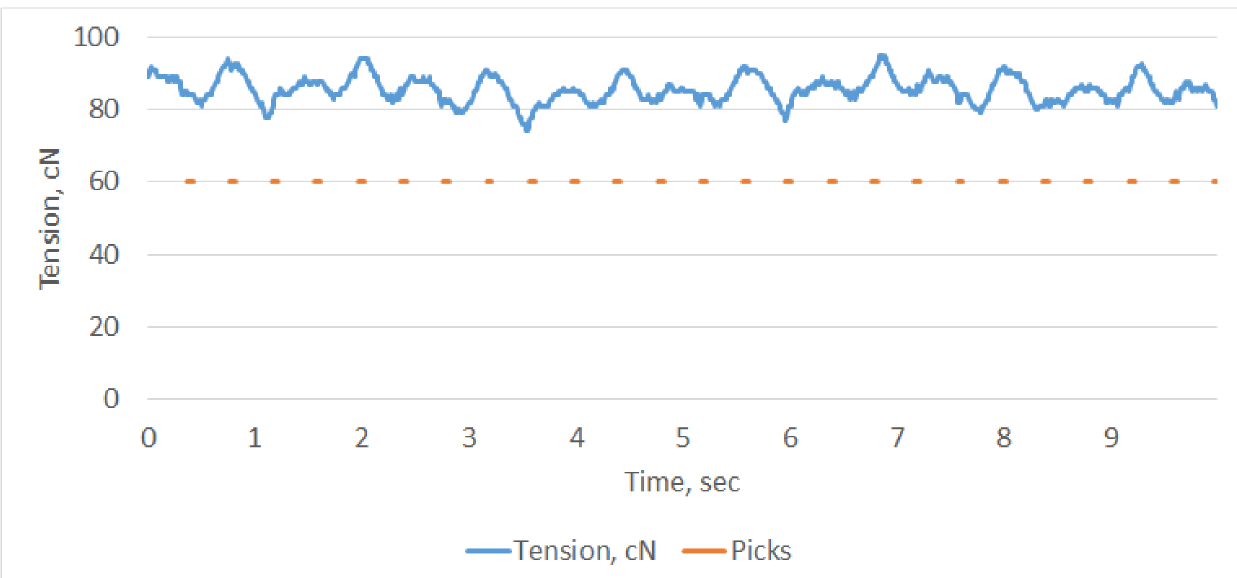

Figure 4.19. Plot between Tension (cN) and time (sec) for loom #22 at position 3

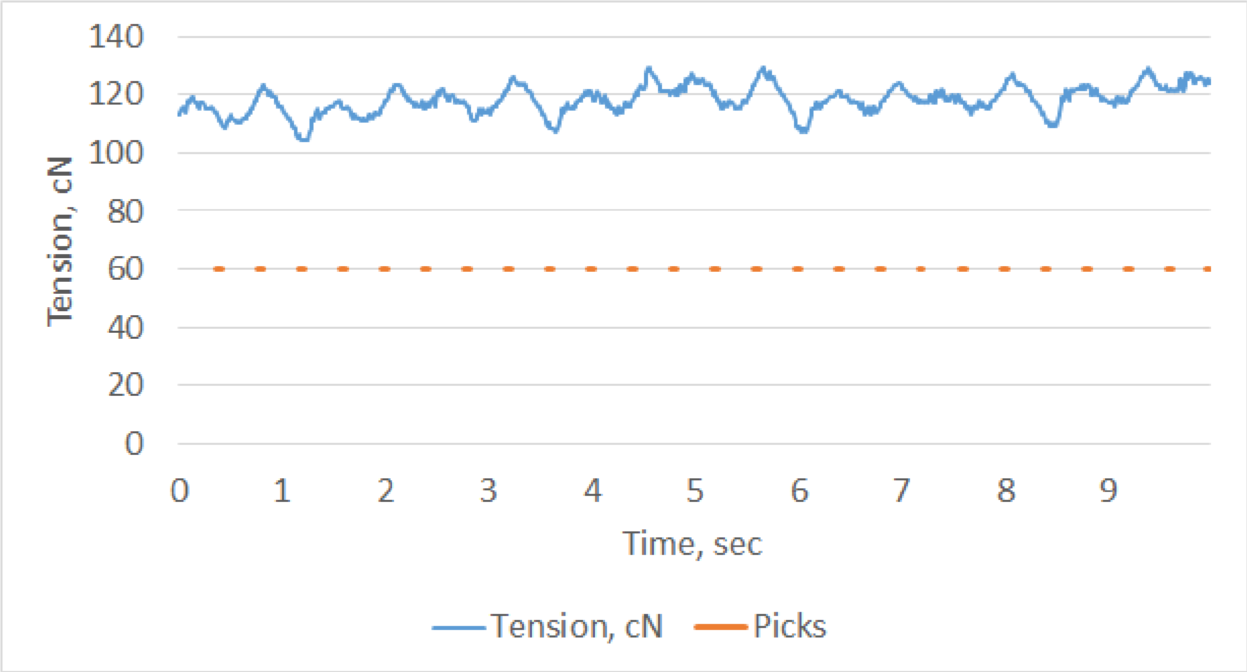

Figure 4.20. Plot between Tension (cN) and time (sec) for loom #22 at position 4

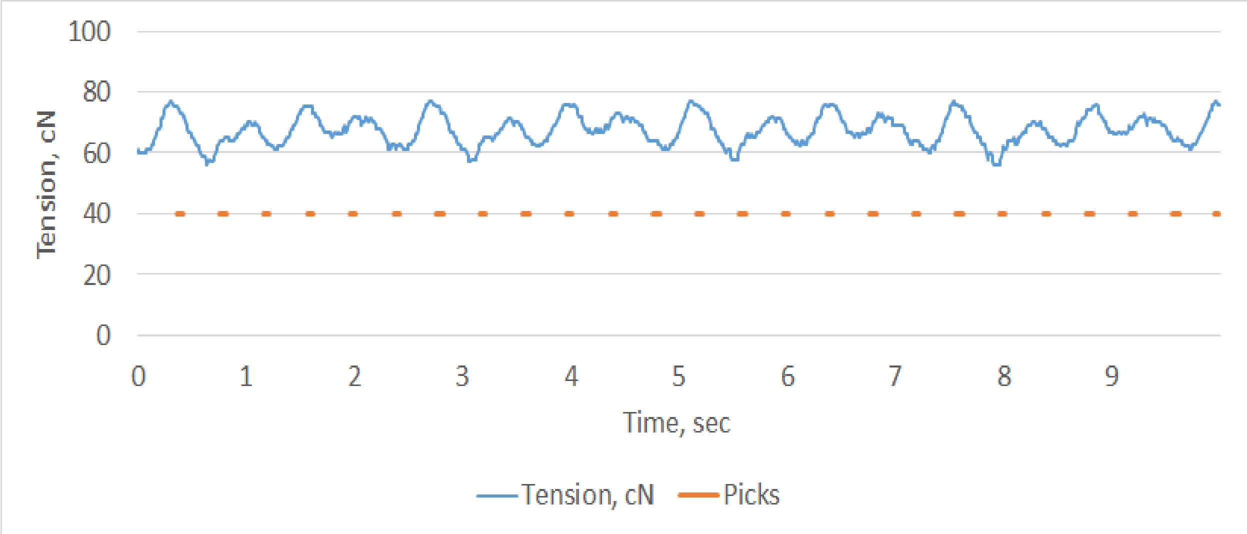

Figure 4.21. Plot between Tension (cN) and time (sec) for loom #22 at position 5

Figure 4.21 shows a comparison of average tension measured at four looms on single warp yarns, using the stand and excluding positions close to the selvedge. The figure also includes the warp radius at the four looms at the time readings were taken. It can be seen that Loom 5 which has the highest warp radius also has the least tension and this confirms the fact that warp tension keeps increasing as warp radius decreases previously discussed in section 4.1.2.

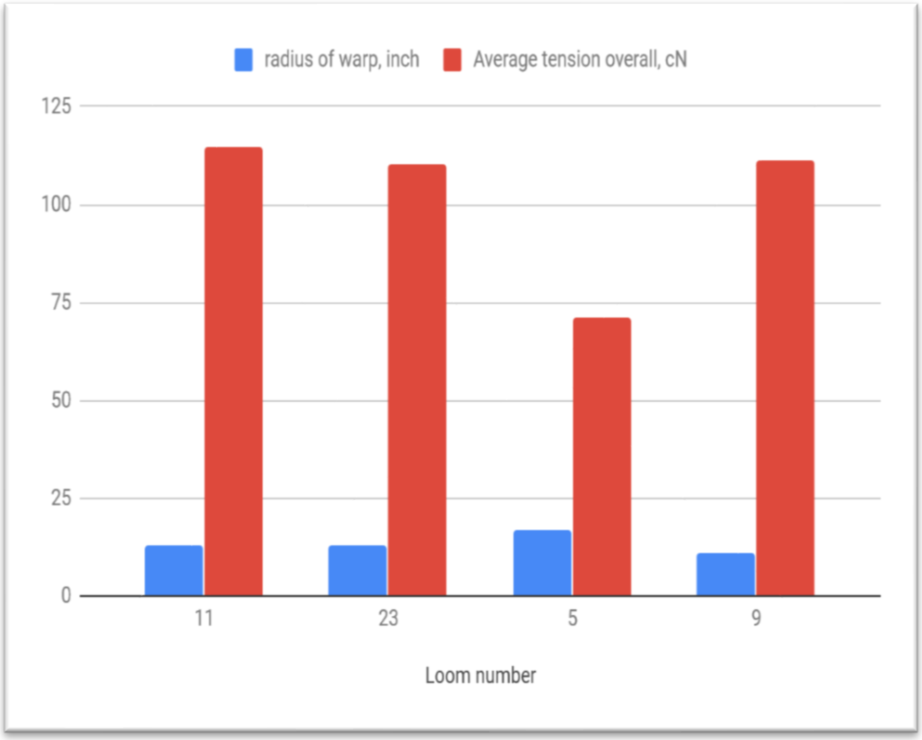

Figure 4.22. Comparison of warp tension with respect to warp radius at different looms

In conclusion Table 4.10 shows the tension values obtained for a single warp yarn (from phase 5 of tension measurement) and those calculated for the whole warp sheet. The accumulator should be able to impart up to a maximum of 750 kN of tension to the full warp sheet for smooth and regular weaving at the looms at P&A.

Table 4.10. Tension values for the whole warp sheet obtained in phase 5

Loom no.	Average warp tension for single yarn, cN	Average warp sheet tension, kN
11	114.46	7.42
23	110.1	7.13
5 (newly tied-in)	71.19	4.61
9	111.40	7.21

CHAPTER 5: MARKET POTENTIAL OF THE NON-STOP TYING-IN PROCESS

In order to evaluate the market potential of Non-stop tying-in process, a number of methods were tried out. The basic approach used was finding out the number of knotting or tying-in machines that were being used by weavers all around the world. This number would give a direct approximation of how big the market for the process could be.

In order to find out the number of tying-in machines being used in the world we tried to find statistical data related to textile machinery in use worldwide. This data could be in the form of yearly reports from textile associations. We also tried reaching out to textile machinery manufacturers and gather information about quantities of tying-in machines they sold in a year.

In the search for relevant textile data, ITMF's International textile machinery shipment report proved to be the most helpful. ITMF publishes the report yearly and it is compiled in cooperation with the world's leading manufacturers of spinning, draw texturing, weaving, knitting and finishing machinery since 1974, their survey shows shipments by country of destination of ring spindles, open-end rotors, draw texturing (false twist) spindles, shuttle and shuttleless looms, large circular and flat knitting machines as well as finishing machinery.

"The stats in ITMF's shipment reports have been compiled with the cooperation of over 200 textile machinery manufacturers. This number entails the Chinese companies included in the so called "districts". The 2017 coverage is virtually complete with the continuation of comprehensive mainland Chinese participation (ITMF, International textile machinery shipment statistics, Vol. 40/2017)". ITMF also explains that "Shipment refers to machinery produced by the participating manufacturers (for both the domestic and export market) which were physically shipped during the year under review and should not be confused with sales or installations (ITMF, International textile machinery shipment statistics, Vol. 40/2017)."

The shipment reports from ITMF had statistics related to the broad categories of textile machineries like spinning, weaving, finishing etc., however there were no stats concerning tying-in machines. Thus, we followed the approach of surveying a number of weaving plants across the US and getting information about how many tying-in machines they have in their plants and how many looms are serviced by them.

Table 5. 1 Companies contacted regarding weaving machinery at their plants

Company name, Location	No. of looms	No. of tying-in machines
Standard Textiles, GA	145	2
Valdese Weavers, NC	150	4
Precision fabrics, NC	300	2
Mt. Vernon Mills, SC	342	5
Culp	40	3
Clear Edge	62	2

After doing this a roundabout number for the number of looms serviced by one tying-in machine was found which came out to be 60. Hereafter, dividing the total number of looms reported in the ITMF report by 60, gave us an estimated number of tying-in machines being used worldwide.

The Installed loom capacity for shuttle less looms in 2016 was reported to be 1,494,197. In addition to this the number of shipments of shuttle less looms made in 2017 was 96,289. For shuttle looms the Installed loom capacity reported in 2015 was 1,296, 952, and the shipments of shuttle looms reported in 2016 and 2017 were 0. Thus, after adding all these numbers, an estimate figure for total number of looms till 2017 came out to be 2,887,438.

Assuming one tying-in machine is used to service 60 looms and dividing the total number of looms by 60, we get a figure for the number of knotting machines in the world as 4,8124

Thus, a good estimate for the number of knotting machines in the world was found to be 45,718-50,530. This number is a good estimate of the number of looms in the world, however this is not an exact number because the reports do not completely comprise of each and every textile machinery manufacturer in the world.

Another approach taken to find the market need for this equipment in numbers was to find the Quantity of Different kinds of woven fabrics produced. The first step for this was to find all the different kinds of woven fabrics produced on the basis of a woven products end use. Woven fabrics or weaving methods where the structure or method makes the fabric specifically suitable for a certain application.

To accomplish this a list offered by the US Department of Commerce categorizing all woven products under different code numbers was consulted. In this list woven fabrics or weaving processes resulting in particular woven fabrics are covered in the sections D03D 1/00 to D03D 27/00. The different categories of woven fabrics produced were categorized as:

Apparel (for shirting, denim, suiting, military uniform fabrics, jacquard fabric), Support Apparel (for pocketing, waistband linings, and interlinings for shirting, Slotted Tapes (one of the most commonly used products to enhance the construction of a waistband, hem or placket)),

Home furnishings (sheeting, mattress pad backings, upholstery decking, blackout curtains, drapes, shower curtains and ticking for pillows and duvets, towels, and infant blankets),

Industrial products (coating substrates such as tapes, fabrics for book bindings, industrial aprons, window shades, buffing cloths, high pressure laminate fabrics, fabrics for paint rollers and for seating surfaces, webbings, Solid woven conveyor belts, Packaging fabrics (for agricultural and industrial markets), Airbag fabrics, Car upholstery, seat belts and seat cover fabrics, fabrics for hoses, Woven filter fabrics), Medical Textiles (Woven grafts, healthcare gowns and scrubs, surgical towels), Geotextiles (Woven Reinforcement Geotextiles, Woven Stabilization and Separation Geotextiles, Woven Filtration Geotextiles), Construction Textiles (Cotton canvas Tarpaulins, HDPE Tarpaulins, Awnings & canopies, Floor & wall coverings), Protective Textiles (Cut protection fabrics, flame retardant fabrics, Military Fabric Products, Ballistic Protection Fabric (Tegris® by Milliken and TenCate Protective Fabrics)), Other (Ballooning fabric, boat covers, Paraglider, parachute and airship cloth, Sail cloth, Sleeping bag fabric). However, the search for exact or even approximate quantities of woven fabric produced was not successful.

In regard to contacting tying-in machine manufacturers the companies listed in table 5.2 were identified. Out of these 13 companies Staubli Corporation had the maximum market share for the device. The big players like Stäubli and Groz- beckert were contacted to gather information on the numbers for tying-in machine yearly sales. Some excerpts from the conversations follow.

Mr. Ludovic Pitrois, who is the North American Textile Division Manager for STAUBLI CORPORATION, said “Stäubli sells approximately 20 knotting machines yearly in the US and 360 yearly worldwide”. He also said that “Stäubli has 60-65% of the market share for this device”.

Mr. Mark Beasley is the Product Manager/Weaving & Spinning at Symtech Incorporated. Symtech Incorporated is responsible for the sale of Groz-Beckert’s Knot master (tying-in machine) in the USA and Canada. He said that on an average they sell around 5 tying-in machines and 5 frames every year in the US and that the lifespan of a tying-in machine could be around 20 years.

Table 5. 2 Tying-in machine manufacturers

China	Jingong Industrial Co., Ltd. Zhejiang Zhejiang Xinben Machinery Co., Ltd.
Switzerland	Staubli (Topmatic & Magma)
Germany	Fischer Peoge Groz Beckert Knotex GmbH & Co KG
Spain	Titan textile Machines
India	Shree Laxmikrupa Industries, Ahmedabad Atex Industries, Ahmedabad Vinitex Engineering Pvt. Ltd., Ahmedabad Jaytex (Jayantilal S. Gandhi and company) Ahmedabad Esstex Engineering and trading Co. Pvt. Ltd., Mumbai Maa Techx Enterprises, Mumbai

CHAPTER 6: CONCLUSION

6.1. Discussion

The Non-stop tying-in process is a new development towards the conventional tying-in process. The idea for this process was developed by Dr. Abdel-Fattah Seyam and Dr. William Oxenham at Wilson College of Textiles at North Carolina State University. The approach of this development was to eliminate the long-term stop practiced currently while tying-in and to allow the weaving process to continue without stopping while the tying-in process is being conducted. The proposed work targeted the development of portable mechanisms that could work with any current automatic tying-in machine.

The non-stop tying-in process was patented, and the initial prototype of the accumulator created for the process was tested in the weaving lab and the process worked successfully. The goal of this research was to evaluate the market potential of the non-stop tying-in process, along with conducting comparison studies for a) time taken during conventional tying-in and during the non-stop tying-in process b) tension in warp yarns during conventional weaving and while weaving with the accumulator.

The market potential was found by using data on loom shipments from ITMF's yearly textile machinery shipment reports and making some calculations based off of an estimate number of tying-in machines used to service a definite number of looms. The final figure for the market potential of the Non-stop tying-in process came up to between 45,000-50,000.

A time study of the conventional tying-in process was also conducted, and it gave a total loom downtime of 374 minutes. Due to iterations and additional parts needed to be made to the design of the accumulator it was not possible to conduct a successful trial of the Non-stop tying-in process in the time frame of this project. Nevertheless, a trial was conducted and has been documented in section 3.2.33 with a clear explanation of all the problems that the team faced along with a list of all the iterations/additions needed to the design.

Tension measurement was an important part of this project and it was done in a total of six consecutive phases that were done over the duration of 9 months. The results obtained have been concisely reported in a number of tables within chapter 4. These measurements also gave the team an estimated figure of the maximum tension level (~750 kN) that the accumulator should be able to impart to the warp tail while feeding it to the loom for weaving.

6.2. Implications

- With the use of non-stop tying-in process, the looms will experience increased weaving efficiency. This increase will be a result of considerable decrease in loom downtime which is a given during conventional tying-in.
- Along with the above two benefits the warp waste produced during non-stop tying-in will also be lesser than during conventional tying-in.
- None of the above implications could be confirmed with data/numbers given the need of iterations in the design of the accumulator as well as the time frame for this project.

6.3. Recommendations for future research

- Conducting time study to compare time taken during the conventional process with the non-stop tying-in process.
- Comparison of warp waste produced in the two processes.
- Conducting a study on the warp yarn tension while the warp is being let off from the accumulator.

- All of these above listed activities were initially supposed to be completed as a part of this project, however, iterations needed in the design led to time restraints that inhibited the team to complete these tasks in the given time frame.
- Another experimental study for warp tension at a weaving plant with more modern looms that have automatic tension control mechanism installed in them would yield better results for getting an estimated overall figure for warp tension in those particular looms.

6.4. Recommendations for future development

- Building an accumulator with tension control. This would allow for easy and consistent let off of accumulated tail warp sheet as feed into the loom.
- Building an accumulator with dynamic/variable tension control (a system that allows the tension level provided by the accumulator to be set according to existing warp tension at different looms).
- Building a set up for narrow weaving looms.
- Building a set up for warp knitting machines.
- Extending the scope of the non-stop tying-in process to carpet weaving.

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APPENDICES

Appendix A: Tension measurements from phase 2

Table A.1. Data collected on single ground warp yarn tension during phase 2 at loom #41

Loom no.	Position	Tension in single ground yarn, g	Average tension for single ground beam yarn, g	Average Tension for Ground Warp Sheet, kg	Minimum Tension for Ground Warp Sheet, kg	Maximum Tension for Ground Warp Sheet, kg
41	1	51.43	56.39	365.42	260.04	545.81
	2	84.23				
	3	65.12				
	4	41.05				
	5	40.13				

Table A.2. Data collected on single ground warp yarn tension during phase 2 at loom #29

Loom no.	Position	Tension in single ground yarn, g	Average tension for single ground beam yarn, g	Average Tension for Ground Warp Sheet, kg	Minimum Tension for Ground Warp Sheet, kg	Maximum Tension for Ground Warp Sheet, kg
29	1	116.5	97.74	633.36	525.40	754.92
	2	103.28				
	3	102.35				
	4	85.49				
	5	81.08				

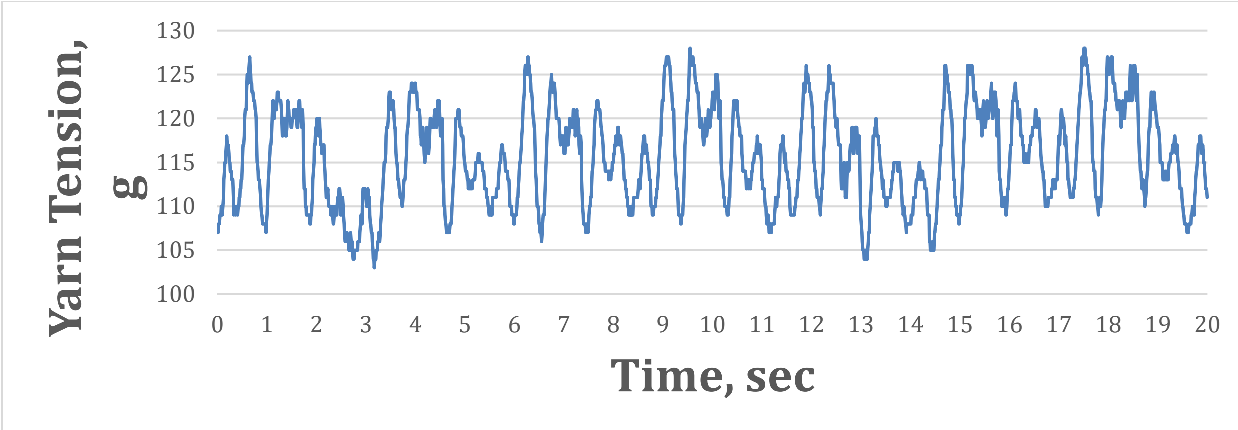

Figure A.1. Plot between tension and time for a single ground warp yarn at loom 29

Table A.3. Data collected on single ground warp yarn tension during phase 2 at loom #1

Loom no.	Position	Tension in single ground yarn, g	Average tension for single ground beam yarn, g	Average Tension for Ground Warp Sheet, kg	Minimum Tension for Ground Warp Sheet, kg	Maximum Tension for Ground Warp Sheet, kg
1	1	89.5	92.11	596.87	579.96	783.30
	2	120.88				
	3	97.85				
	4	104.28				
	5	48.04				

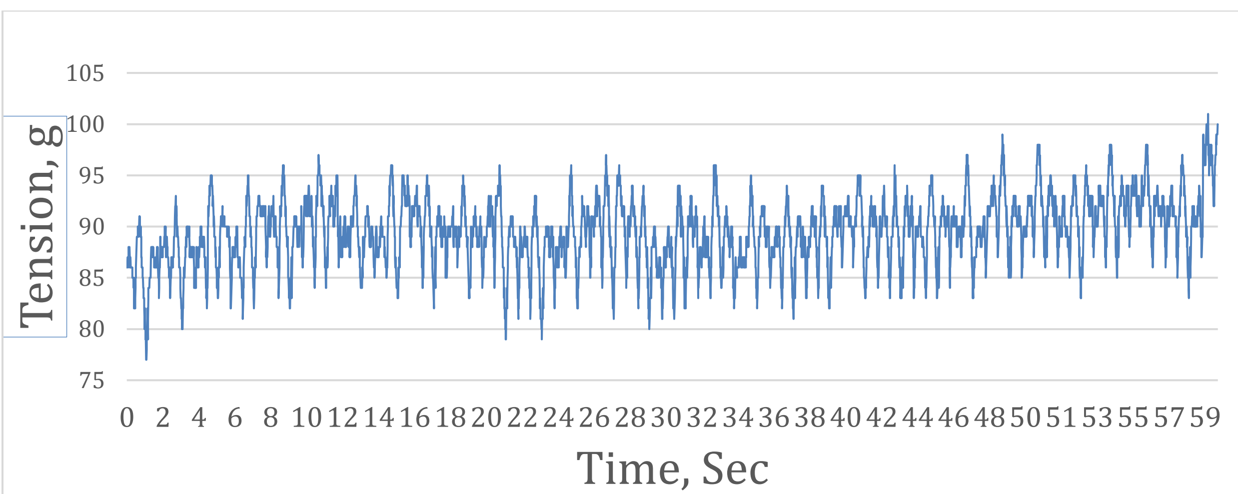

Figure A.2. Plot between tension and time for a single ground warp yarn at loom #1, position 1

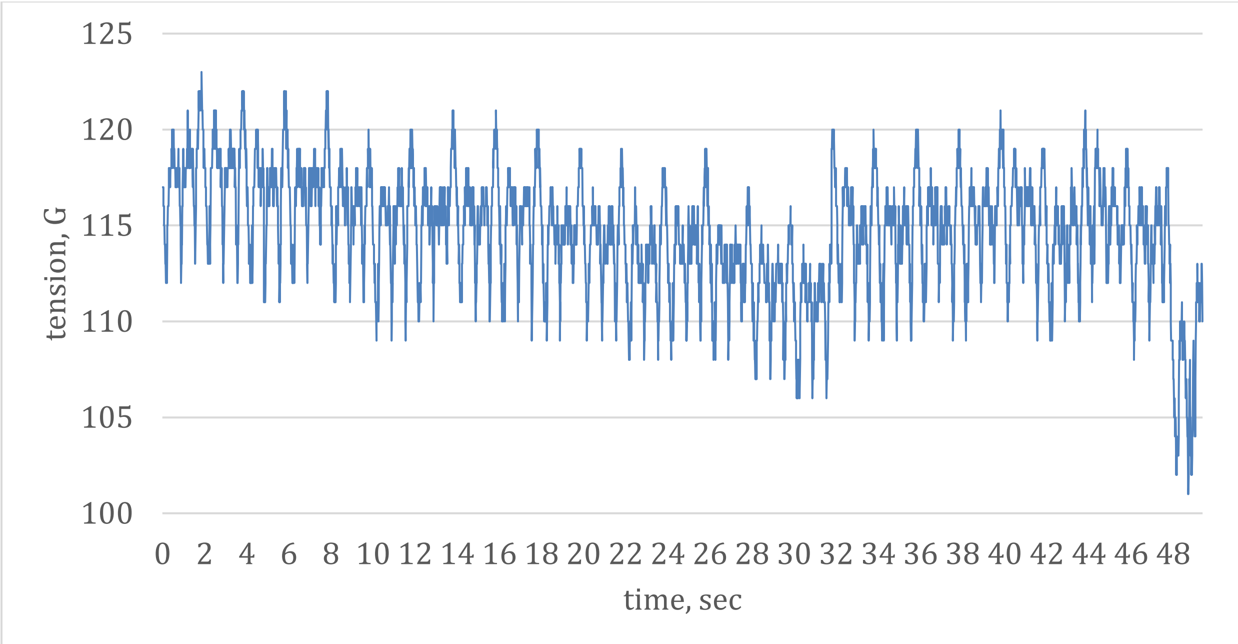

Figure A.3. Plot between tension and time for a single ground warp yarn at loom #1, position 2

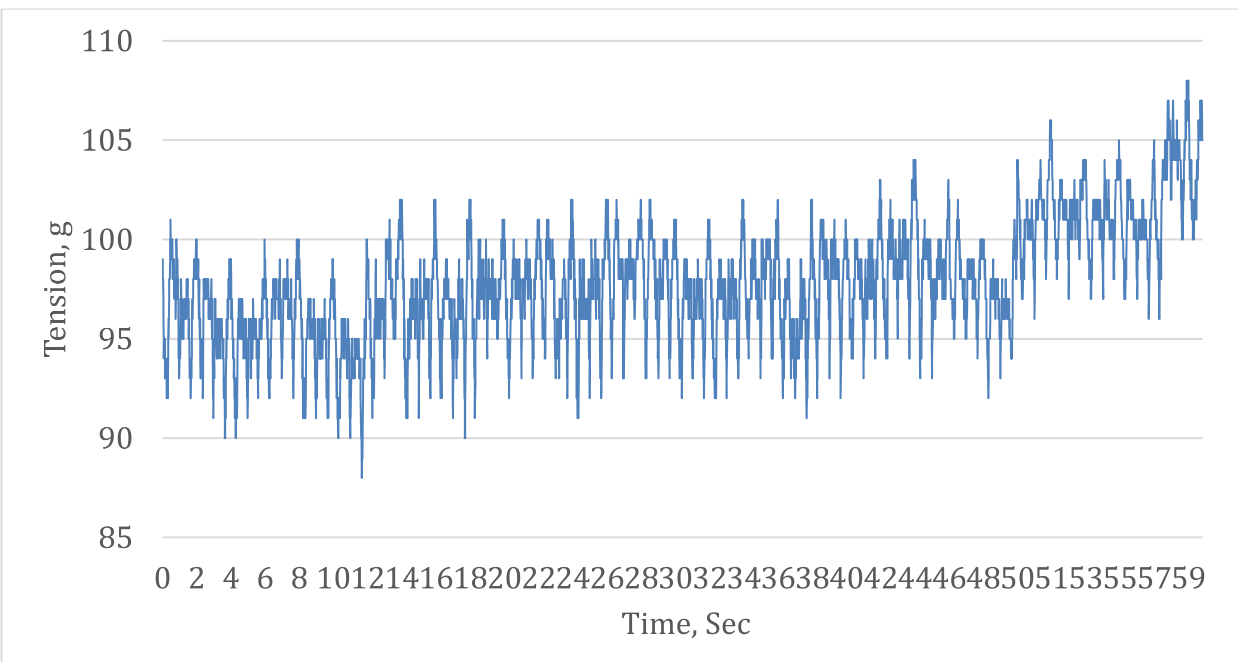

Figure A.4. Plot between tension and time for a single ground warp yarn at loom #1, position 3

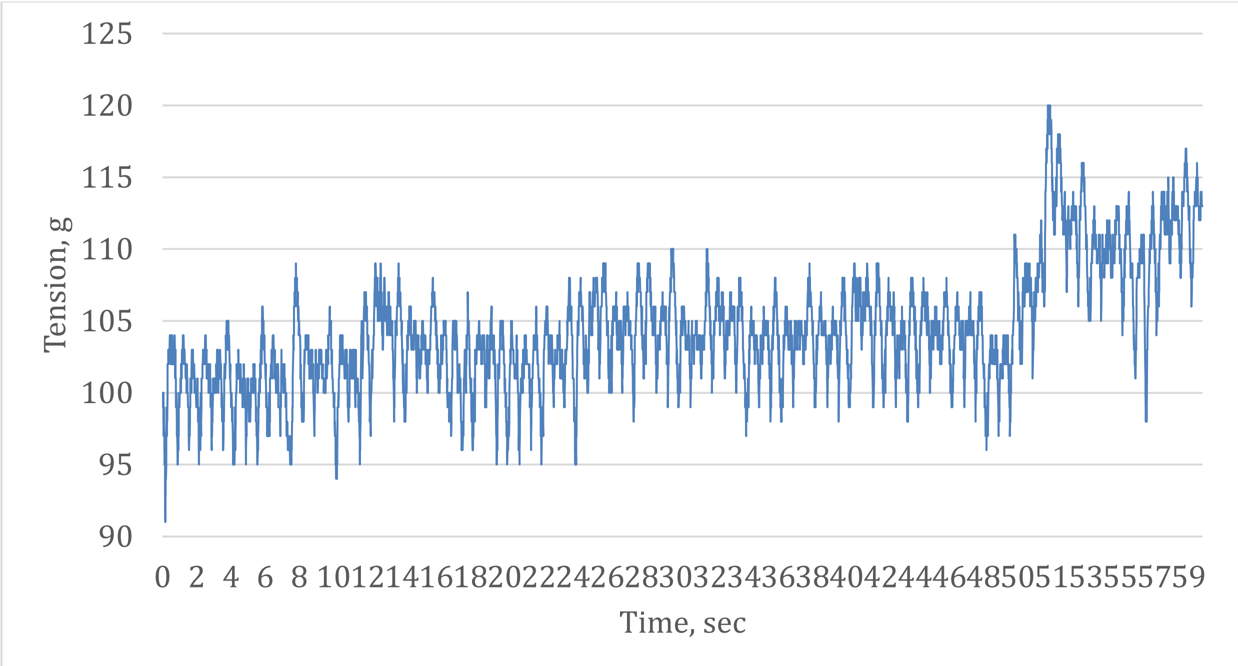

Figure A.5. Plot between tension and time for a single ground warp yarn at loom #1, position 4

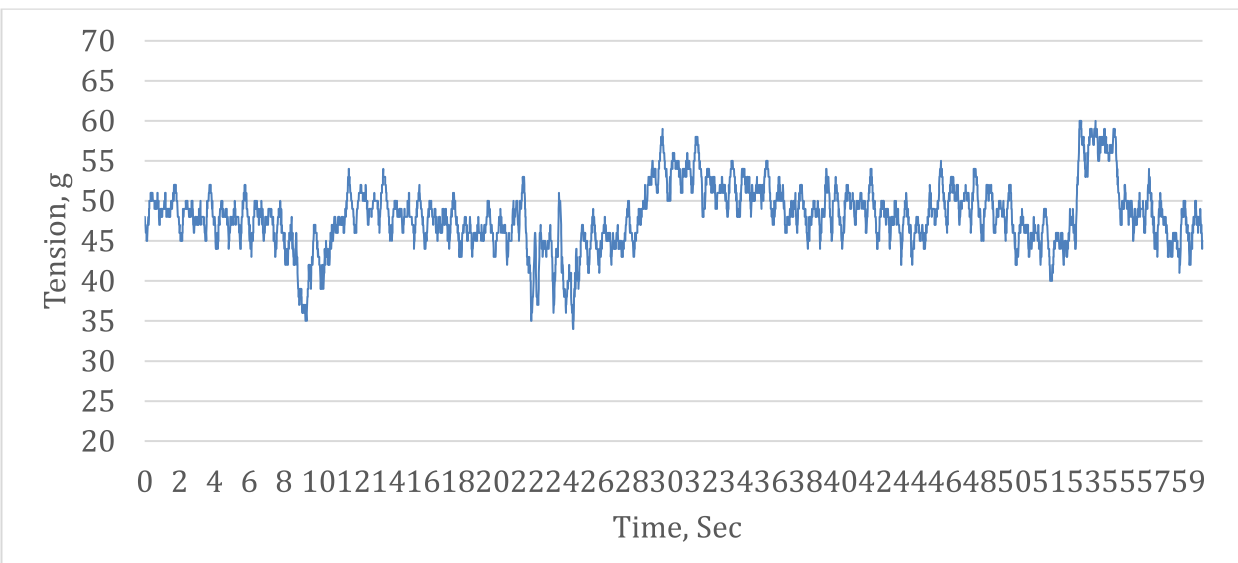

Figure A.6. Plot between tension and time for a single ground warp yarn at loom #1, position 5

Table A.4. Data collected on single ground warp yarn tension during phase 2 at loom #135

Loom no.	Position	Tension in single ground yarn, g	Average tension for single ground beam yarn, g	Average Tension for Ground Warp Sheet, kg	Minimum Tension for Ground Warp Sheet, kg	Maximum Tension for Ground Warp Sheet, kg
135	1	86.38	78.27	507.19	403.96	623.05
	2	76.59				
	3	96.15				
	4	62.34				
	5	69.89				

Table A.5. Data collected on single ground warp yarn tension during phase 2 at loom #136

Loom no.	Position	Tension in single ground yarn, g	Average tension for single ground beam yarn, g	Average Tension for Ground Warp Sheet, kg	Minimum Tension for Ground Warp Sheet, kg	Maximum Tension for Ground Warp Sheet, kg
136	1	64.86	84.84	549.75	488.01	733.15
	2	82.38				
	3	113.14				
	4	88.5				
	5	75.31				

Table A.6. Data collected on single warp yarn tension during phase 2 at loom # 3

Loom no.	Position	Tension in single ground yarn, g	Average tension for single ground beam yarn, g	Average Tension for Ground Warp Sheet, kg	Minimum Tension for Ground Warp Sheet, kg	Maximum Tension for Ground Warp Sheet, kg
3	1	85.13	99.518	644.87664	469.8648	877.33
	2	100.49				
	3	135.39				
	4	104.07				
	5	72.51				

Table A.7. Data collected on single pile 1 warp yarn tension during phase 2 at loom #41

Loom no.	Position	Tension in single Pile 1 yarn, g	Average tension for single pile 1 yarn, g	Average Tension for Pile 1 Warp Sheet, kg	Minimum tension for Pile 1 Warp Sheet, kg	Maximum tension for Pile 1 Warp Sheet, kg
41	1	11.98	20.63	10.40	4.31	30.70
	2	8.55				
	3	9.77				
	4	60.92				
	5	11.91				

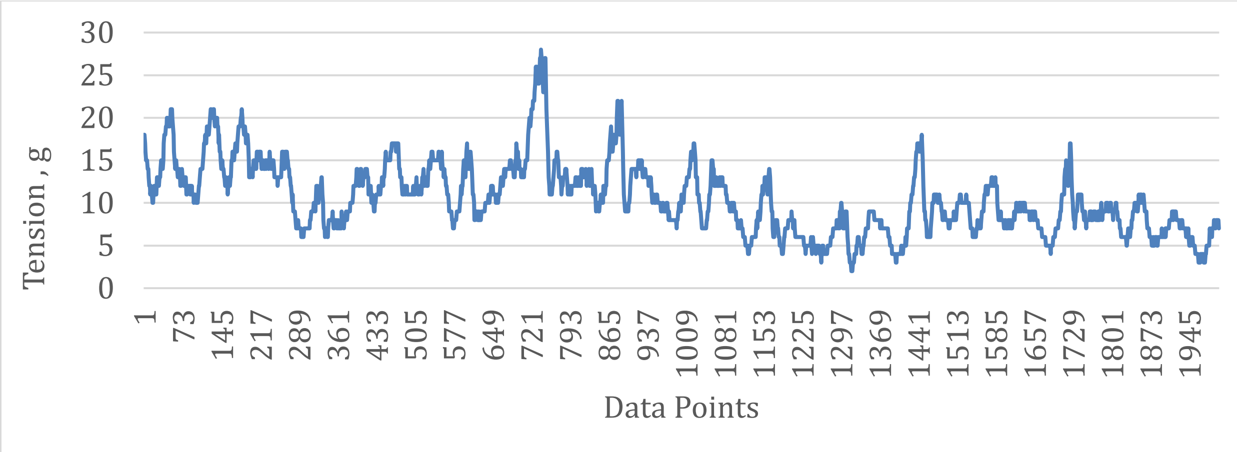

Figure A.7. Plot between tension and time for a single pile 1 yarn at loom 41

Table A.8. Data collected on single pile 1 warp yarn tension during phase 2 at loom #29

Loom no.	Position	Tension in single Pile 1 yarn, g	Average tension for single pile 1 yarn, g	Average Tension for Pile 1 Warp Sheet, kg	Minimum tension for Pile 1 Warp Sheet, kg	Maximum tension for Pile 1 Warp Sheet, kg
29	1	15.06	11.63	5.86	4.02	7.59
	2	14.79				
	3	9.89				
	4	7.98				
	5	10.44				

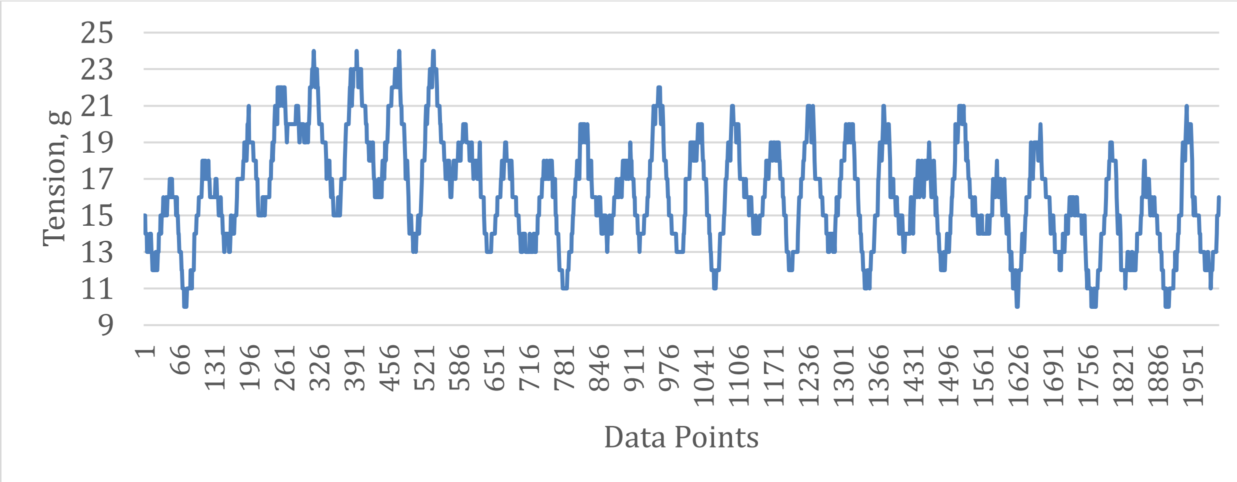

Figure A.8. Plot between tension and time for a single pile 1 yarn at loom 29

Table A.9. Data collected on single pile 2 warp yarn tension during phase 2 at loom #41

Loom no.	Position	Tension in one single pile 2 yarn, g	Average tension for single pile 2 yarn, g	Average Tension for Pile 2 Warp Sheet, kg	Minimum Tension for Pile 2 Warp Sheet, kg	Maximum Tension for Pile 2 Warp Sheet, kg
41	1	13.17	16.02	8.07	6.21	8.34
	2	12.32				
	3	13.44				
	4	24.6				
	5	16.55				

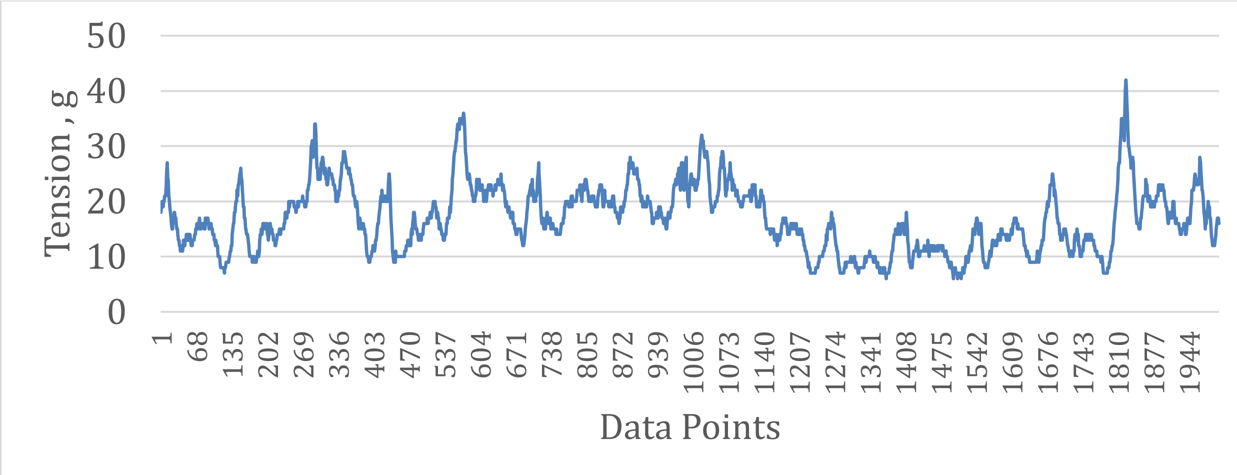

Figure A.9. Plot between tension and time for a single pile 2 yarn at loom 41

Table A.10. Data collected on single pile 2 warp yarn tension during phase 2 at loom #29

Loom no.	Position	Tension in one single pile 2 yarn, g	Average tension for single pile 2 yarn, g	Average Tension for Pile 2 Warp Sheet, kg	Minimum Tension for Pile 2 Warp Sheet, kg	Maximum Tension for Pile 2 Warp Sheet, kg
29	1	8.6	8.71	4.39	3.50	5.36
	2	9.6				
	3	6.94				
	4	10.64				

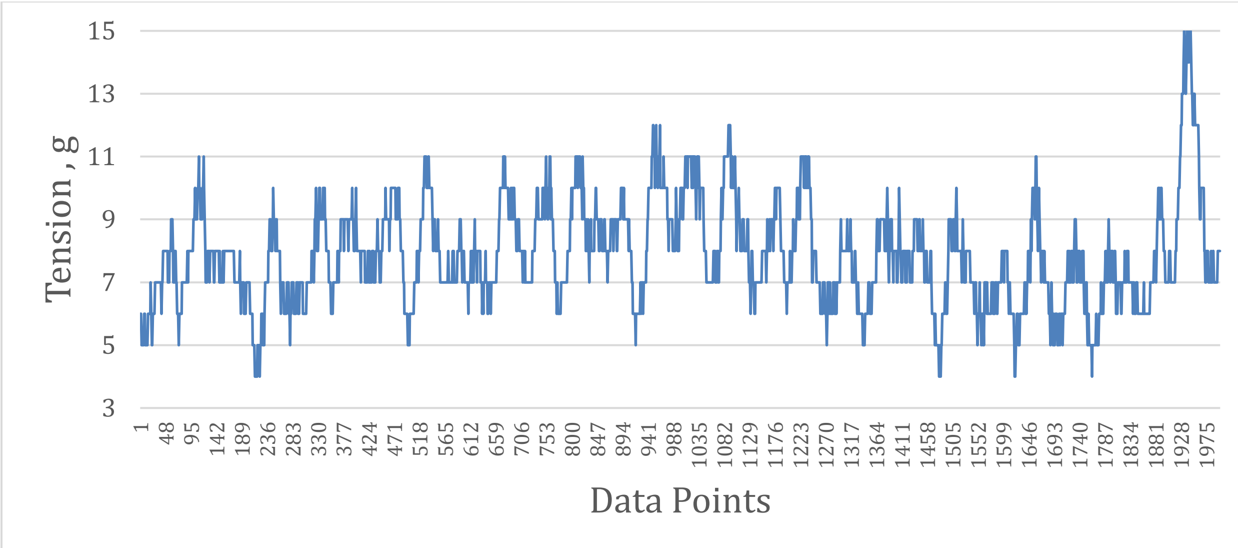

Figure A.10. Plot between tension and time for a single pile 2 yarn at loom 29

Appendix B: Tension measurements from phase 3

Table B.1. Tension measurements for group of 4 ground warp yarns

Loom number	**Tension (Grams)**					**Average Tension for a group of 4 ground yarns, (Grams)**	**Tension/yarn, (Grams)**
	P1	P2	P3	P4	P5		
26 (Newly Installed beam)	335.64	350.82	378.79	375.51	479.52	384.056	96.014
41	142.62	281.74	329.33	258.61	262.49	254.958	63.7395
8	363.2	364.55	388.57	380.02	388.23	376.914	94.2285
136 (new beam)	195.14	298.02	324.24	317.4	213.76	269.712	67.428
3 (beam about to finish)	262.6	406.19	447.86	430.5	401.27	389.684	97.421
1 (beam about to Finish)	279.7	405.33	414.51	383.35	250.14	346.606	86.6515

Appendix C: Tension measurements phase 4

Table C.1. Tension measurement on ground warp yarns using stand for holding tension meter at loom #11

Loom number	Position, inch	Average tension at each position, cN	Std. dev	CV, % for each position	Max tension recorded at each position, cN	Min tension recorded at each position, cN	Number of ground warp yarns	Warp sheet tension, kN
11	1	83.39	5.01	6.008	95	71	6480	5.2
	17	82.58	3.64	4.408	92	72		
	33	83.72	2.74	3.273	90	78		
	49	78.48	3.24	4.128	87	70		
	65	74.34	5.84	7.856	86	61		
	Average tension overall, cN 80.502							

Table C.2. Tension measurement on ground warp yarns using stand for holding tension meter at loom #23

Loom number	Position, inch	Average tension at each position, cN	Std. dev	CV, % for each position	Max tension recorded at each position, cN	Min tension recorded at each position, cN	Number of ground warp yarns	Warp sheet tension, kN
23	1	8.08	2.98	36.881	15	2	6480	2.58
	17	31.43	2.55	8.113	38	24		
	33	26.36	1.92	7.284	31	21		
	49	73.16	2	2.734	78	67		
	65	60.37	2.91	4.820	66	52		
	Average tension overall, cN 39.88							

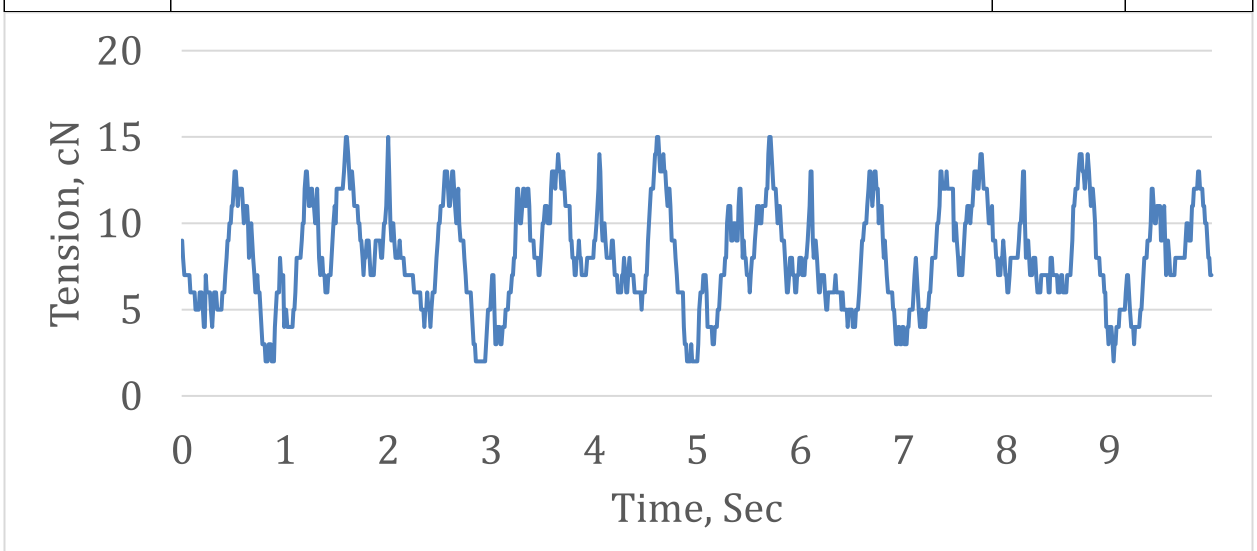

Figure C.1. Plot between tension and time for a single ground warp yarn at loom 23, Position 1

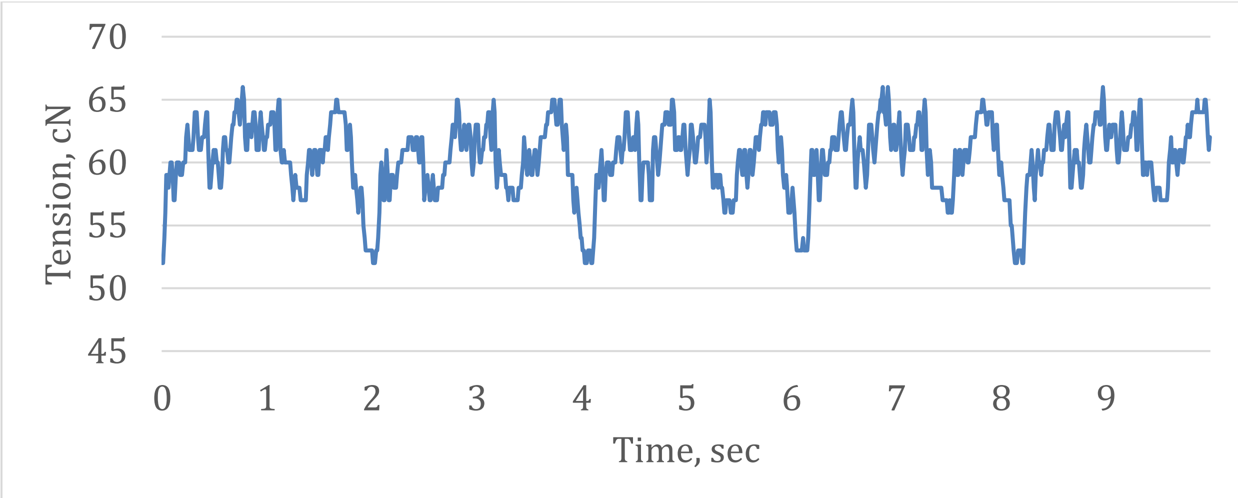

Figure C.2. Plot between tension and time for a single ground warp yarn at loom 23, Position 2

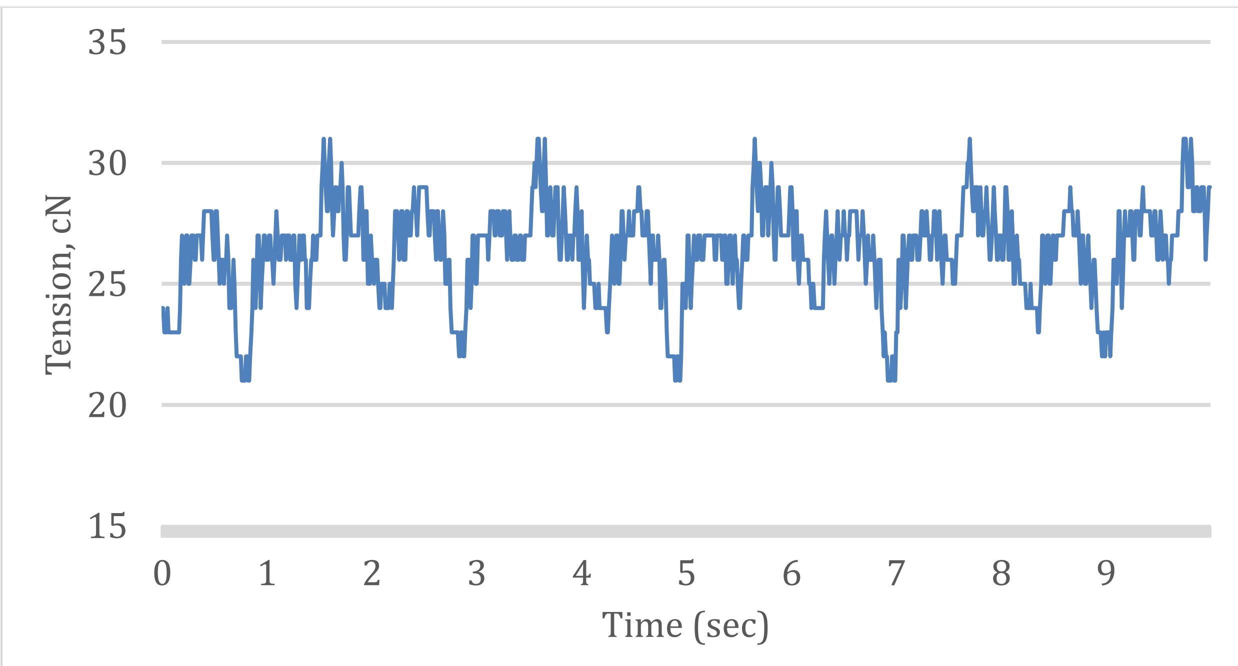

Figure C.3. Plot between tension and time for a single ground warp yarn at loom 23, Position 3

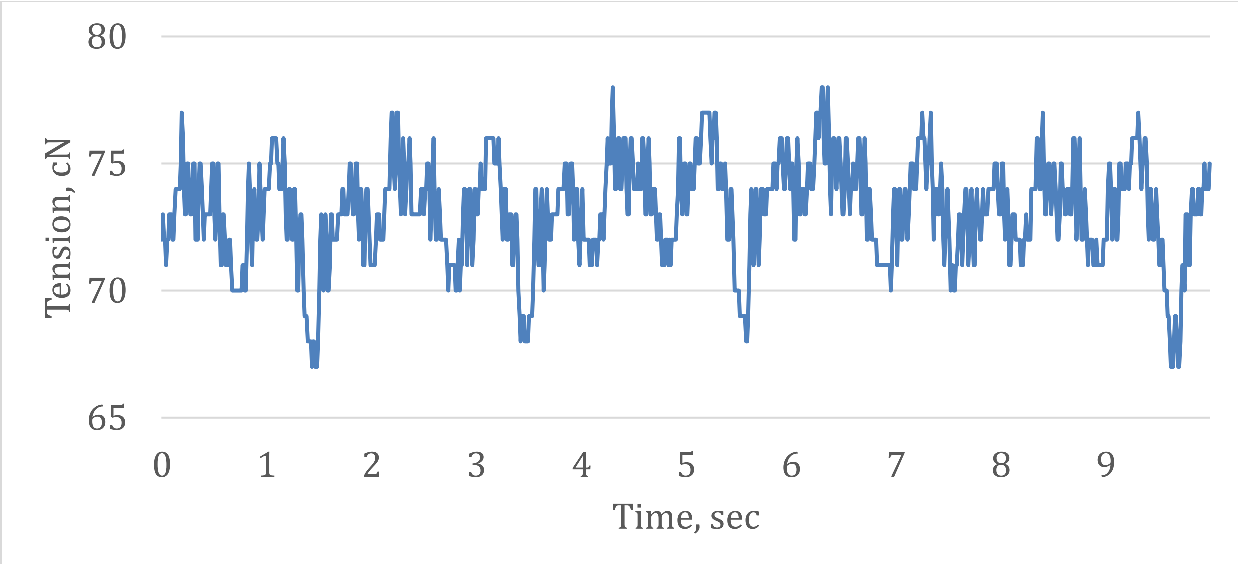

Figure C.4. Plot between tension and time for a single ground warp yarn at loom 23, Position 4

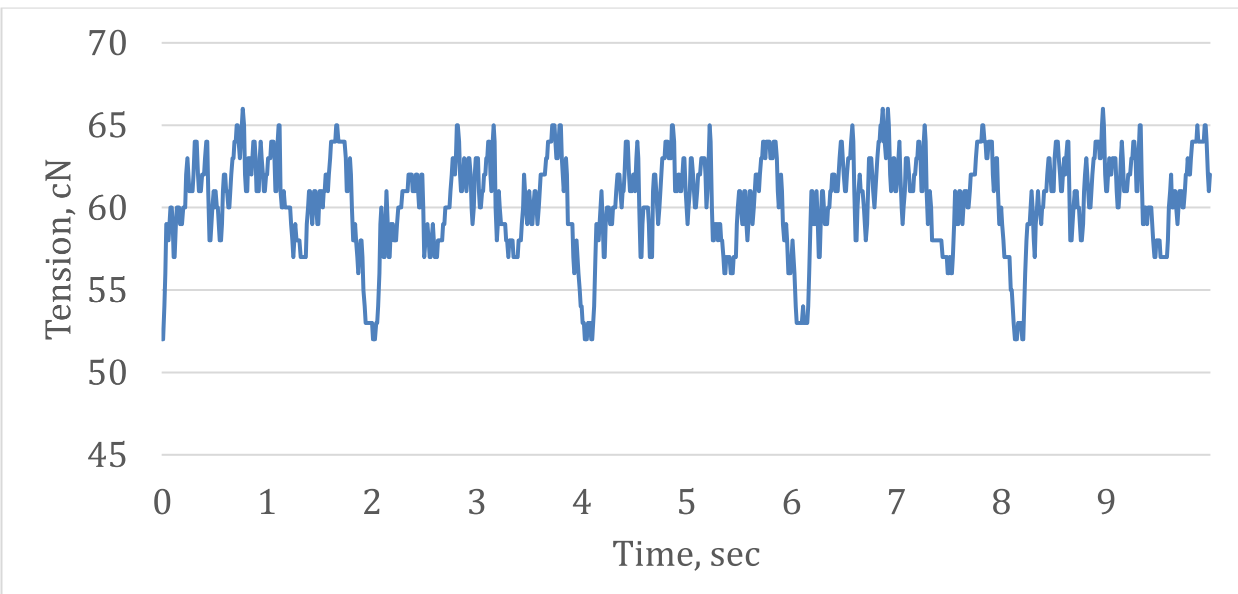

Figure C.5. Plot between tension and time for a single ground warp yarn at loom 23, Position 5

Table C.3. Tension measurement on ground warp yarns using stand for holding tension meter at loom #5

Loom number	Position, inch	Average tension at each position, cN	Std. dev	CV, % for each position	Max tension recorded at each position, cN	Min tension recorded at each position, cN	Number of warp yarns	Warp sheet tension, kN
5	1	4.41	2.57	58.277	10	0	6480	2.12
	17	47.42	3.17	6.685	54	41		
	33	45.64	3.08	6.748	54	37		
	49	39.92	2.93	7.340	47	34		
	65	26.25	3.53	13.448	35	19		
	Average tension overall, cN 32.728							

Table C.4. Tension measurement on ground warp yarns using stand for holding tension meter at loom #22

Loom number	Position, inch	Average tension at each position, cN	Std. dev	CV, % for each position	Max tension recorded at each position, cN	Min tension recorded at each position, cN	Number of warp yarns	Warp sheet tension, kN
22	1	91.59	5.95	6.496	104	75	6480	5.86
	17	89	4.13	4.640	99	77		
	33	85.68	3.57	4.167	95	74		
	49	118.07	4.77	4.040	129	104		
	65	67.44	4.76	7.058	77	56		
	Average tension overall, cN 90.356							

Appendix D: Tension measurements phase 5

Table D.1. Tension measurement on ground warp yarns using stand for holding tension meter, (excludes positions close to selvedge) at loom # 11

Loom number	position, inch	Average tension at each position, cN	Std deviation	CV, % for each position	Max tension recorded at each position, cN	Min tension recorded at each position, cN	Number of warp yarns	Warp sheet tension, kN
11	5	128.31	4.66	3.6318	140	118	6480	7.42
	15	116.25	4.09	3.5183	127	105		
	25	124.41	3.88	3.1187	135	113		
	35	116.37	3.49	2.9991	126	105		
	45	106.47	2.6	2.4420	115	100		
	55	104.32	3.83	3.6714	115	94		
	60	105.09	3.6	3.4256	116	96		
	Average tension overall, cN 114.46							

Table D.2. Tension measurement on ground warp yarns using stand for holding tension meter, (excludes positions close to selvedge) at loom # 23

Loom number	position, inch	Average tension at each position, cN	Std deviation	CV, % for each position	Max tension recorded at each position, cN	Min tension recorded at each position, cN	Number of warp yarns	Warp sheet tension, kN
23	5	96.44	4.16	4.3136	107	82	6480	7.13
	15	122.36	3.3	2.6970	132	111		
	25	122.77	3.78	3.0789	133	111		
	35	109.11	2.68	2.4562	117	100		
	45	112.45	2.61	2.3210	120	103		
	55	103.93	3	2.8866	112	94		
	60	103.64	3.98	3.8402	114	90		
	Average tension overall, cN 110.1							

Table D.3. Tension measurement on ground warp yarns using stand for holding tension meter, (excludes positions close to selvedge) at loom # 5

Loom number	position, inch	Average tension at each position, cN	Std deviation	CV %	Max tension recorded cN	Min tension recorded cN	Number of warp yarns	Warp sheet tension, kN
5, newly tied-in	15	55.83	4.87	8.7229	60	45	6480	4.61
	25	84.5	2.57	3.0414	89	78		
	35	51.23	4.29	8.3740	61	45		
	45	108.9	3.96	3.6364	103	119		
	55	55.5	3.99	7.1892	52	40		
	Average tension overall, cN 71.19							

Table D.4. Tension measurement on ground warp yarns using stand for holding tension meter, (excludes positions close to selvedge) at loom # 9

Loom number	position, inch	Average tension at each position, cN	Std deviation	CV, % for each position	Max tension recorded at each position, cN	Min tension recorded at each position, cN	Number of warp yarns	Warp sheet tension, kN
9	5	114.12	5.88	5.1525	128	101	6480	7.22
	15	116.58	4.8	4.1173	130	105		
	25	114.9	3.86	3.3594	125	105		
	35	107.28	3.96	3.6913	118	97		
	45	107.13	3.93	3.6684	118	97		
	55	109.97	5.03	4.5740	123	96		
	60	109.8	5.88	5.3552	125	93		
	Average tension overall, cN 111.40							

Appendix E: Tension measurements phase 6

Table E.1. Tension measurement on warp yarns during the warping process

	Position	Average Tension, cN	Std. deviation	CV%	Maximum tension, cN	Minimum tension, cN
Creel#2	Back of creel	31.86	1.59	4.991	38	13
	Front of creel	40.03	1.15	2.873	44	36
	Between creel and guide plate	42.33	1.23	2.906	47	38
	Between collection point and beamer	51.65	2.19	4.240	59	43