BEHAVIOR OF CONCRETE MEMBERS WITH COMPRESSION MECHANICAL SPLICE

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ABSTRACT

Mechanical bar splices or what commonly known as couplers, have been used in reinforced concrete structures for a long time to directly connect steel bars in lieu of conventional lap splicing. Generally, when mechanical splices are mentioned, the focus drawn toward the tensile properties of the splice and neglect the compression side, because almost all the time it is the most critical stress at any given section. But what if this was not the case and the section is subjected to compressive stress only, Using the same splice that are mint to satisfy a more critical and Stricter case (tensile stress) with the same precautions for a more forgiven case (compression stress) will result in over conservative implementation of the splice. This research will focus on the compression side as the main and critical stress, to develop an economical splice that can satisfy the design requirement without any unnecessary precautions.

This thesis will evaluate the potential application of mechanical reinforcing bar splices that are intently used to resist mainly compression stresses, and what if it is feasible to use it in the construction market. An experimental investigation was performed to determine what is the best performing mechanical splice of many that vary in shape and mechanism, but come to gather of being cheap, easy to install and questionable in tension. Twenty-six specimens in total were fabricated and examined. The specimens' tests were divided in to two phases, The first phase consist of seventeen specimens that will be tested in a progressive sequence, where will change the coupler conditions (length and bolts spacing); aiming to narrow the coupler shape, length and installation condition. This phase will test the couplers bare with it been submerged in concrete; to have a clear illustration on how the coupler will perform later on if it were to be chosen to continue in the following tests in the second phase, where it will be used in a reinforced concrete member.

The second phase of testing will consist of Nine specimens, we will take the chosen coupler from the previse phase of tests and utilize it in a real-world application, in reinforced concrete member. The first three specimens will be the control specimen, the mechanical threaded spliced specimen and a lap spliced specimen, where the couplers that are focused on in this thesis will not be used. The rest will incorporate the chosen coupler from the First phase of Tests. The fourth, fifth and sixth specimens will study the stirrups density twice. The seventh and eighth specimens will change the staggering distance. And the last specimen we will change the main RFT diameter, as a trail to find the limits for the selected coupler.

The test results shows that the members using the selected splice increased the capacity of the member. Therefore, research in this point should continue to have a clear understanding for all aspects and behavior, that hopefully lead to adopting it in a broader scale. The test results show that the members with bars that were spliced with the chosen sleeve coupler performed better than all of the legacy bar connecting method (lap and mechanical) and better than a member with a plain continuous bar. Changing the staggering distance has almost no effect on the capacity of the member neither on it is mode of failure, and that is cannot be said about the density stirrup. as predicted, increasing the stirrups density will increase the member capacity period. Conclusion, the sleeve compression splice is a valid cheaper and easier alternative for the legacy expensive couplers in some use cases that mainly resist compression stresses.

1. INTRODUCTION

Reinforced concrete has been used in the construction field for decades. The reinforced concrete structure cannot be constructed in monolithically along the whole structure but in stages. However, all the structures after completion must behave in a monolithic manner. Due to manufacturing and transportation considerations, the length of the reinforcing bar is limited, therefore, splicing of reinforcing bars is unavoidable.

Generally, splices can be classified into Four types: lap splice, mechanical splice, welded splice & gas pressure welded splice. Lap splice is by far the most common and the simplest method to use. However, many researches show that the lap splice is weak under seismic load and it is structurally less reliable. Where, its performance is hindered by the concrete cover and the concrete compressive strength. Moreover, the added difficulties in both design and construction, the hustle of not exceeding the maximum requirement of steel to concrete ratio, the essential space that is needed for concrete placing and the fear of honeycombing of concrete caused by a steel congestion.

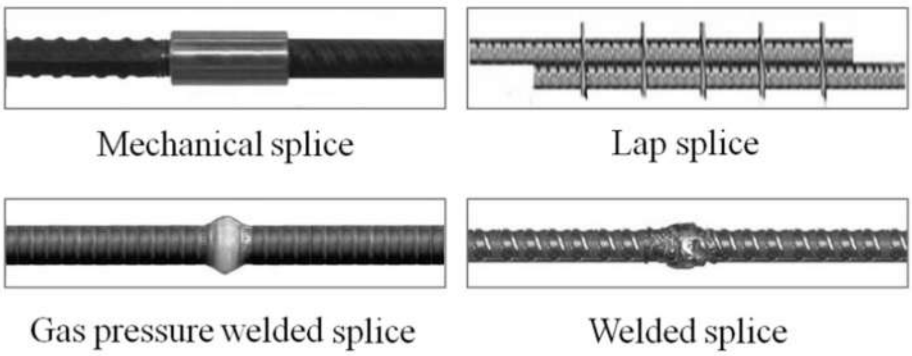


Figure 1. 1 Types of Rebar Splices

On the other hand, the other types of splices can overcome these disadvantages of the lap splice and save the costs of the calculation process and a good chunk of materials. But they also have a disadvantages of their own, such as: the need for an experienced crew, the additional time needed for carrying out the connection procedure or installing the splice device, the prepping of the reinforcement bars in advanced and the possessing of special devices and tools to manufacture the connection or to install the splice.

Broadly, when mechanical splices are mentioned, the focus is directed on their tensile properties and their requirement, whereas, the compressive side is completely neglect. And this is justified, because the tension stresses are mainly resisted by the steel rebars. However, what if the main stresses on the member are compressive and the tension stresses are minimal, using a splice device that is meant to satisfy the tensile stresses will result in an over conservative implementation of splices, as satisfying tensile requirement is more restricted and harder than compression one.

The Concrete Reinforcing Steel Institute (CRSI – USA) classify the mechanical splices into two categories, tension-compression mechanical splice (full mechanical splice) and compression-only mechanical splice, as seen in the figure 1.2 respectively.

Figure 1. 2 Mechanical Splices Classification

Full mechanical spliced rebar behaves in a matter similar to a plain rebar, as it can transfer both the tension and compression force. Whereas, the compression-only mechanical splice is designed and fabricated to transfer the compression force only between the two connected rebars. In applications where the member is subjected to mainly compression loads with minimal to no tension loads, employing a full mechanical splice that require a more costly and intensive measures will result in a low value engineering implementation for the splice, whereas, using an adequately sufficient and cheaper compression-only splice will be more favourable, and this thesis will focus on this type, the compression-only splice.

Using the compression-only splice does not mean that the member or structure does not have any capabilities to resist any tension forces. Whereas, the American Concrete Institute (ACI 318-19) required some mandatory condition that have to be met to provide a minimum tension safety value. This minimum safety value broadens the application that can utilize such splice. Moreover, the compression splice can be used in in cooperation with other types of full mechanical splice if the section forces does not require full splicing for all rebars.

Structural system, member location, member orientation and building proportions (length-width-hight) to name a few, are some factors that regulate the use of compression splices. One example on that, is The Pentagon Building. Where, the assigned contractor company (John

Mcshain) directed the use of LENTON (company that specialize in advance mechanical rebar splicing system) compression splice on some columns (figure 1.3).

Figure 1. 3 Precedent for The Usage of Compression Splice

Other use case that might benefit from the compression splice, are the cast in situ piles (figure 1.4). Where, the main forces on the member are compression forces, accompanied with some minor tension forces that can be resisted by the minimum safety margins provided by the splice.

Figure 1. 4 Ex of Compression Splice Usage

The splice can also help with the accelerated construction project, that employ precast members. Ether for the precast member itself or the cast in situ deck, utilizing the splice in the compression zone will speed the installation prosses and reduce the cost.

Figure 1. 5 Ex of Compression Splice Usage

Objective and Organization

The general azimuth for the compression-only mechanical splice is still surrounded by doubt and disbelief to this day. Where, it is scarcely used globally and might never been used locally before. This thesis aims to help clear any confusion about utilizing this type of splice in reinforced concrete members, and pave the way for greater adaptation for it in construction work. This research will touch on the different types of compression-only mechanical splice and their distinctive characteristic and limitation to identify the most convenient one. Then, members that utilize the chosen splice will be compared to a control member first followed by comparing it to members that use the legacy method of connecting reinforcement (mechanical threaded splice and lap splice). Other factors will also be studied, Like stirrups density and stagging distance. Employing the same splice for an altered diameter will also be examined.

The thesis will carry out an analytical and lab work investigation that will be organized as follows:
As previously laid out The First Chapter presented a brief background on the subject and the proposed use case. The Second Chapter will discuss the bases from the code followed by the literature review. Fabrication and a lap comparison between the different compression splice (bare with no concrete) will be carried out in The Third Chapter. The Fourth Chapter will be the preparation and testing of nine reinforced concrete specimens, Where, the selected splice from the previous chapter will be utilized in some specimen and not in the other to compare between them, followed by studying the effect of stirrups density and the staggering spacing. Lastly, The Fifth Chapter will present the conclusion and summery of this thesis.

2. LITERATURE REVIEW

The construction field has many written and unwritten taboos when it comes to mechanical splices. Where, mechanical splices can not be used in the connection between two precast members, it also cannot be used in the plastic hinge zone of a structure, and locally, the compression-only mechanical splice is not allowed at all in the reinforced concrete work. The anxiety of utilizing the compression-only splice is always blamed on the construction field difficulties and mishaps that might lead to a poor-quality splice, that will result in less optimum rebar connection.

But this can be easily refuted after knowing that the lap splice itself (which is the most popular bar connection method) performance is hindered by the produced concrete quality. So, no matter how good the lap splice is, if the strength of the produced concrete was poor, then the lap splice performance will be poor, and vice versa. Unlike the full mechanical splices (carry tension and compression) that must deliver full performance even before the casting of concrete, the compression-only mechanical splice is different in this regard. Where, the mechanize of the splice is similar to the lap splice; that they are both can provide some performance by themself, but for the full capability of the splice, casting and curing of concrete is a must.

The enhancing of the load carrying capacity for the member, the rationalization of the reinforcement steel and the ease of installation are some of the crucial reasons that help the compression mechanical splice to gain attentions in the resent years. Only an accurate and careful analysis for both, the construction application requirements, and for the mechanical splice capacity and its limitation, can increase the adoption on this splice type. This thesis will focus on the analysis of the mechanical splice.

2.1 Mechanical Splices in Codes

The ACI 318 code in the 439 committee[1.2], have talked at length about the utilization of the mechanical splices in construction and provided a general consideration, design requirement and installation description for multiple types of splices. From a function stand point, this committee divided the mechanical connection in to three basic types: (1) compression only mechanical connection (or end-bearing mechanical connection), (2) tension only mechanical connection, (3) tension-compression mechanical connection (or Full mechanical splice). The choice of using a mechanical splice over a lap splice, can turn from useless to feasible option to a necessity depending on the conditions and situation of the connection. One example, is the tension continuity between an old and new construction, having a developed length to satisfy tension requirements for a lap splice can be proven to be difficult or un obtainable, thus, the usage of mechanical splices is now a necessity not a luxury.

2.1.1 General Consideration

Throughout the prosses of bridging the rebars and establishing the connection, some physical futures that might influence the performance for both the splice device and the installation equipment must be met.

2.1.1.1 Spacing and Cover requirements for the parallel bars must have a minimum clear distance of no less than a nominal diameter of the rebar or 1 inch (25 mm) (choose the bigger), and for the column the minimum increases to 1.5 times the nominal diameter of the rebar or 1.5 inch (38 mm) (choose the bigger). For spliced bars, table 2.1 and 2.2, display the proper clear distance between the rebars. Meeting the minimum clearance might be difficult due to the bigger outside diameter of the splice, thus, the staggering of the splices might be the solution.

2.1.1.2 End Alignment matching, End preparations or any special prosses for the tow rebar ends that the engineer and the crew should be aware of, for the mechanical connection to function right. For example, the code specifies in section 12.16.4.2 that the rebar end that mint to be connected with an end-bearing splice must retain a surface within 1.5 degree of square relative to the longitudinal axis.

2.1.1.3 Remove Coating of Reinforcement. If the reinforcement bars are coated with epoxy or zinc, the mechanical connection for coated bars is similar to the uncoated bars; because the coating must be completely removed before the installation of the splice, with at least 2 inches (50mm) beyond the end of the splice device.

2.1.1.4 Coordination of The Field Erection process. In some cases, the staggering of the splice device is necessary, having a preassembled steel cage with the staggering in mind might prove to be un obtainable. This will mean that there will be considerable difference between the members that utilizes the splice and those who don't. Therefore, it is must be taken into account the added time and the required equipment for the installation of the splice.

2.1.2 Design Requirement

Mechanical splices are a very broad and complex topic. Codes in general, try to draw boundaries to achieve a minimum connection strength. The ACI does not go in details for the requirements for all types of splices, rather, it has defined a minimum strength for the connection for the most common type of splices, the full mechanical splice. Where it stated in section 12.14.3.4, "A full mechanical connection shall develop in tension or compression, as required, at least 125 percent of specified yield strength F_y of the bar". This does not mean that the ACI neglect the rest of the splices, it is just approach it from a physical stand point and installation guidelines, which will be discussed in upcoming section.

2.1.3 Mechanical Connection, Devices and Installation

2.1.3.1 Tension-Compression Mechanical Splice

All manufactural must fabricate their full mechanical splices to achieve the ACI requirement for such type. Which is "A full mechanical connection shall develop in tension or compression, as required, at least 125 percent of specified yield strength F_y of the bar". Moreover, The ACI describe nine types of these device in terms of description, capability of connecting different bar sizes and etc…. As seen in table 2.1.

Table 2. 1 Tension-Compression Mechanical Splices

		Cold-swaned steel coupling sleeve (Fig. 3.3.1*)	Cold-swaged coupling sleeve with threaded ends acting as a coupler (Fig. 3.3.2 and 3.4.4)	Extruded steel coupling sleeve (Fig. 3.3.3)	Hot-forged steel coupling sleeve (Fig. 3.3.4)	Grout-filled coupling sleeve (Fig. 3.3.5)	**Coupler for thread-deformed* rebars (Fig. 3.3.6 and 3.4.3)**	**Steel-filled coupling sleeve (Fig. 3.3.7)**	Taper-threaded steel coupler (Fig. 3.3.8)	Integrally-forged coupler with upset NC thread (Fig. 3.4.1)	Three-piece coupler with NC thread (**Fig. 3.3.9, 3.4.2.1,** and* 3.4.2.2)	Steel coupling sleeve with wedge* (Fig. 3.5.1)
Coupling sleeve/ coupler	Bar size range	#3-#18	#3-#18	#5-#18	#5-#18	#5-#18	**#6-#18**	**#4-#18**	#4-#18	#4-#11	**#4-#18[†]**	#3-#7
	Connects different bar sizes	Yes	Yes	Yes	Yes	Yes	**Yes**	**Yes**	Yes	Yes	Yes	No
Clear spacing required between adjacent connections	#18	**2¾** in.	**1½ in.**	**5⅞** in.	1 1/2 d_b	4.72 **in.**	1 1/2 d_b	1 1/2 d_b	**1½** in.	NA	**1½** in.	NA
	#14	**2¾** in.	1 in.	4 1/2 **in.**	1 1/2 d_b	3.90 **in.**	**1½** d_b	1 1/2 in.	**1½ in.**	NA	1 in.	NA
	#11	2 in.	1 in.	4 1/2 in.	**1½** d_b	3.50 in.	**1½** d_b	1 1/2 d_b	1 1/2 in.	1 1/2 in.	1 in.	NA
# 18 coupling sleeve/ coupler installation requirements (normal)	Minimum dowel projection	12 in.	None	21 3/4 in.	(V)-18 in. (H)-20 in.	18 in.	4 and **7½ in.[‡]**	3 7/8 in.	**3½** in.	NA	4 in.	NA
	Coupling sleeve/ coupler length	12 in.	14 in.	**12¼** in.	9 in.	**36¼** in.	8 and 15 **in.[‡]**	7 in.	**6¼** in.	NA	6 in.	**NA**
	Coupling sleeve/ coupler maximum diameter/across corners	**3¾** in.	3 5/8 in.	**3¼ in.**	**4¼** in.	**4¾** in.	3 1/2 in.	3 5/8 in.	3 in.	NA	3 in.	**NA**
	Coupling sleeve/ coupler side wall thickness (nominal)	**⅝** in.	**5/16** in.	**⅝** in.	½ in.	½ in.	**⅝** in.	½ in.	Varies Min. **⅜** in.	NA	NA	**NA**
Bar-end preparation	Cut square within 1 1/2 deg	No	No	No	No	No	No/Yes*	No	No	No	No	**No**
	Cleaning-special cleaning	No	No	No	Remove loose particles	No	No	Remove concrete and loose rust	No	No	No	**No**
	Predrying/heating	No	No	No	**Yes, coupling sleeve**	**No**	No	Yes	No	No	No	**No**
	Thread cutting/ rolling	No	No	No	**No**	**No**	No	No	Yes**	No	Yes	**No**
	Special coating removal (epoxy, zinc)	No	No	No	**Yes**	**No**	No	Yes	No	No	No	No
Installation tools	Hand-held tools adequate	No	Yes	No	**No**	**Yes**	Yes:<#11 No:>#11	No	Yes	Yes	Yes	No
	Special tools required	Yes	No	Yes	Yes	**Yes, grout pump**	Yes	Yes	No	No	No	Hydraulic wedge driver
	Weather restrictions	No	No	No	**Bars must be dry**	**No**	No	Bars must be dry	No	No	No	No
	Fire precaution	No	No	No	**Yes**	**No**	No	Yes	No	No	No	No
	Ventilation required	No	No	No	**No**	**No**	No	Yes	No	No	No	No

2.1.3.2 Compression-Only Mechanical Splice

The ACI does not state any special requirement for utilizing such splices, but it requests a physical and arrangement consideration to take place, and they are as follows: **2.1.3.2.1 Tensile Safety Value**. If the stresses due to factored load are compressive, end-bearing splice shall be permitted provided that the continuing bars in each face of the column can fulfill:

Continuing bars =0.25*fy* * the area of the vertical reinforcement along that face

This can be achieved through staggering of the splices or an additional bar strapped at the splice location.

2.1.3.2.2 Staggering. Many researches have shown that the staggering is not necessary for the full mechanical splice, in the contrary, this type of splices obligate staggering. This also add to the tensile safety value and help with clearance between the rebars. **2.1.3.2.3 Square Cut Ends**. For all end-bearing splices except for the steel-filled coupling sleeves, the rebar ends must be saw cut, or by any method, within 1.5 degree of square relative to the longitudinal axis. This means, that the ends must be within 3 degrees from full bearing.

2.1.3.2.4 Ensuring Centricity. The bearing splice must be capable of ensuring the centricity of the two connected rebars throughout the construction process.

The ACI describe four types of these device in terms of description, capability of connecting different bar sizes and etc…. As seen in table 2.2.

Table 2. 2 Compression-Only Mechanical Splices

		Boiled steel sleeve			
		Solid-type steel coupling sleeve (Fig. 3.2.1.1*)	Strap-type steel coupling sleeve (Fig. 3.2.1.2)	Steel-filled coupling sleeve (Fig. 3.2.2)	Wedge-locking coupling sleeve (Fig. 3.2.3)
Coupling sleeve	Bar size range	#8-#18	#7-#18	#11-#18	#7-#18
	Connects different bar sizes	Yes	Yes	Yes	Yes
Clear spacing required between adjacent connections	#18	1½ d_s	1½ d_s	1½ d_s	1½ d_s
	#14	1½ d_s	1½ d_s	1½ d_s	1½ d_s
	#11	1½ d_s	1½ d_s	1½ d_s	1½ d_s
#18 coupling sleeve installation requirements (normal)	Minimum dowel projection	6 in.†	6 in.	1¾ in.	6 in.
	Coupling sleeve length	12 in.	12 in.	3 in.	12 in.
	Coupling sleeve maximum diameter/across corners	2¾ in.	4 in.	3¼ in.	2¾ in.
	Coupling sleeve side wall thickness (nominal)	Nil	Nil	5/16 in.	Nil
Bar-end preparation	Cut square within 1½ deg	Yes	Yes	No	Yes
	Cleaning-special cleaning	No	No	Remove concrete and loose rust	No
	Predrying/heating	No	No	Yes	No
	Thread cutting/rolling	No	No	No	No
	Special coating removal (epoxy, zinc)	No	No	Remove coatings 2 in. above sleeve	No
Installation tools	Hand-held tools adequate	Yes	Yes	No	Yes
	Special tools required	No	No	Yes	No
	Weather restrictions	No	No	Bars must be dry	No
	Fire precaution	No	No	Yes	No
	Ventilation required	No	No	Yes	No

2.2 Harry B. Lancelot (1985)

A paper was published by Dr. Harry B. Lancelot (1985) [3] contain the findings from his research on the subject of mechanical splices of reinforcement bars. The paper discussed different types of splices, both, full mechanical and compression-only splices.

2.2.1 Compression-only Splices

Three types of compression-only splices where studied, (a) bolted flange coupling sleeves, (b) bolted straps coupling sleeves and (c) cylindrical sleeve with opening, as seen in figure 2.1. The three of them work through friction-clamping interlock, where, the two bars have to be aligned, followed by tightening the sleeve, ether by the bolts action like sleeve (a) and (b), or by wedge action like sleeve (c).

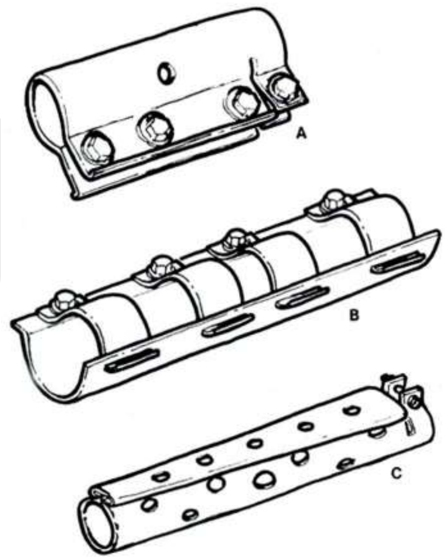


Figure 2. 1 Splices Used by Harry B. Lancelot

The research also emphasizes on the importance of the rebar end cut angle. Where, the angle between the two connected bars must be within 3 degrees from complete bearing. Tensile forces and the clearance between bars to name a few, are some of the reasons and situation that this type of splices is not suitable for, and a full mechanical splice should be used.

2.2.2 Tension-compression splices

Where pretty much all of the compression-only splices rely on friction-clamping interlock mechanism, the tension-compression splices (or full mechanical splice for short) work throughout multiple and different mechanism, thus, the wide varieties of the available types of splices, and the following will list a few.

2.2.2.1 Threaded Couplers

One of the oldest and most common why to splice rebars is the mechanical threaded coupler. The threads ether parallel or tapered and their numbers, spacing and depth depends on the bar diameter and the design loads, as seen in figure 2.2. This type is one of the easiest to install, and generally does not require a lot of precaution and experience to maintain a high-quality control over the connection, and the result is a connection with a behaviour similar to a plain bar. However, this type of splices adds another layer of complexity. Where, the process of threading the rebars ends will take place in the shop or in site. In shop, the process will require a previous knowledge of the number and lengths of the rebars that is need to be spliced, plus the hustle of transferring them to the construction site with no damage to the thread. And in the site, this will require a special machinery that to thread the rebars ends. Parallel or taper, the tapering threads helps with aligning the two rebars, ease the inserting of the rebar into the coupler and distribute the stresses along a bigger area compare to the parallel threads, but, again, tapering might require a machinery that is just not available in the construction site.

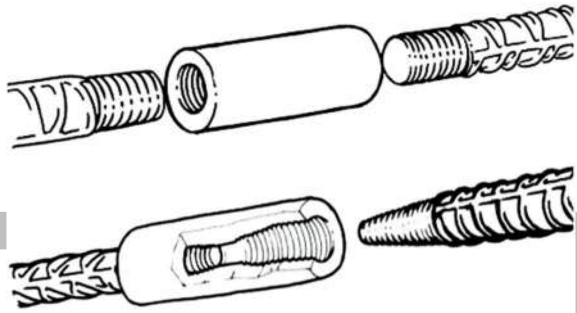


Figure 2. 2 Mechanical Threaded Couplers

2.2.2.2 Metal Filled Sleeves

Likewise, this type of splices is also common and accepted commercially. The coupler it self is fabricated with internal reps, and the rebars are also have external deformation, injecting the molten metal filler into the coupler with the rebar inside will solidify the connection creating a mechanical interlock, figure 2.3.

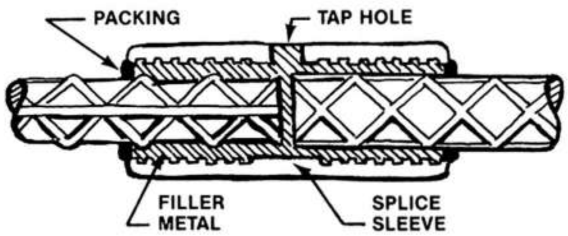


Figure 2. 3 Metal Filled Sleeves

The splice also can be utilized for compression-only application, with a reduction in the coupler length compare to the tension applications. The splice also can fulfil either 125 percent yield stress or a full ultimate stress.

The paper also describes in length other types of splices, but this will be beyond the purpose of this thesis.

2.3 Tazarv and Saiidi (2016)

A research that has been conducted by Tazarv and Saiidi (2016) [4] discussing the mechanical splices for reinforced bars and their effect on the behaviour of concrete column members when it is incorporated them. For the mechanical splice to be incorporated in a plastic hinge region the research recommends a minimum requirement that have to be met:

1- $L_{sp} \leq 15\ d_b$ Where: L_{sp}: mechanical splice total length.
d_b: is the smaller diameter out of the two bars.

2- If the bar is spliced, regardless of the type of, the bar should be fracture away from the coupler region, and only ASTM A706 should be used.

The research also continues on studying the deformation of the splice and it is stress-strain model. Contrary to common conception, when a deformation occurs due to tension stresses, the elongation will not be distribution evenly along the whole length of the rebar and the coupler. Rather, the coupler will be divided in to two parts, a rigid part and a relatively flexible part.

The relatively flexible part will deform and elongate due to stresses, and the rigid part will not contribute to the total elongation of the connection. The rigid part can be defined as the length of the anchorage between the coupler and the bar. The study also used a new term, which is the coupler rigid length factor, which is a value that represent the percentage of the coupler that will contribute in the overall elongation for the connection, and it is known through experiments. The tests results have been rounded up to extrapolate two equations that relate between coupler strain in reference to the unspliced bar strain:

$$\frac{\varepsilon_{sp}}{\varepsilon_s} = \frac{L_{cr} - \beta L_{sp}}{L_{cr}}$$

$$\frac{\varepsilon_{sp}}{\varepsilon_s} = \frac{(1 - \beta) L_{sp} + 2\alpha d_b}{L_{sp} + 2\alpha d_b}$$

Where: L_{cr}: The Coupler Region

L_{sp}: Coupler Length

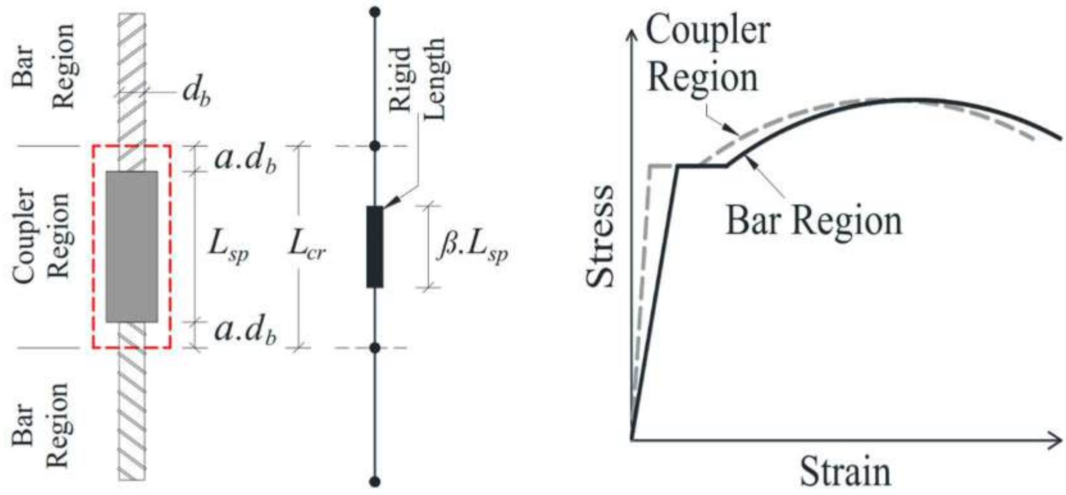
d_b: Bar Diameter

ε_{sp}: Coupler Region Strain

ε_s: Reinforced Bar Strain

β: Coupler Rigid Length Factor

Figure 2.4 shows the stress strain curve for the splice device itself. From the curve, it should be taken into consideration that the coupler is as strong or stronger than the connected bars. If not, then, this coupler is not acceptable.



Coupler Region | Stress-Strain Model for Couplers

Figure 2. 4 Stress-Strain Curve for Mechanical Splices by Tazarv and Saiidi

On that note, knowing the β for a mechanical splice will capacitate the generation of the stress- strain curve for it without the need for a lap experiment.

2.4 Harber et. al. (2014)

An experimental test conducted by Harber et. al. (2014) [5]studying the incorporation of splices in the connection of precast members. The test consisted of four specimens, the specimen consists of a column and footing connection, two specimens were to be directly connected without pedestal, and the other two, were to be connected by a precast pedestal, Figure 2.5.

Headed Reinforcement Connection | Grouted coupler Connection

Figure 2. 5 Precast column Coupler in column-footing connection by Haber

The tests were a cyclic loading test, Figure 2.6 display the Force-Drift curve for all four specimens. The test results showed that the two specimens that incorporated the coupler had a drift ratio of 6 % after completing one full cycle, where, the other two cast in situ specimens got 10 % adrift ratio after the same duration. Consequently after these results, it was concluded the it is both safe and practical to utilize mechanical splices in the connections of precast members.

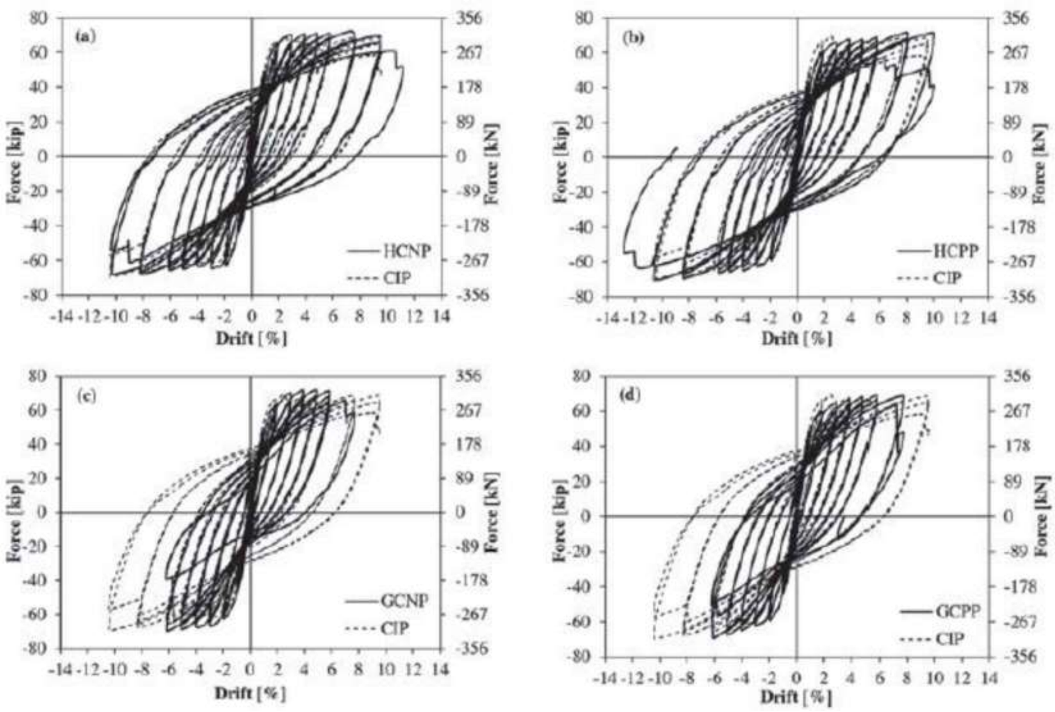


Figure 2. 6 Force Drift Relation of Different Specimens by Haber

2.5 Bompa and ElGhazouli (2017)

511 mechanical splices specimens were tested by Bompa and ElGhazouli [6]. They tested the specimens under monotonic-cyclic load until failure. 244 out of the 511 were mechanical with interlock mechanism (UHC, SWC, PTC, RTC, BLC, OBLC, TTC, OSWC, MFC), and the rest 267 specimen were grouted couplers (GSC), Figure 2.7.

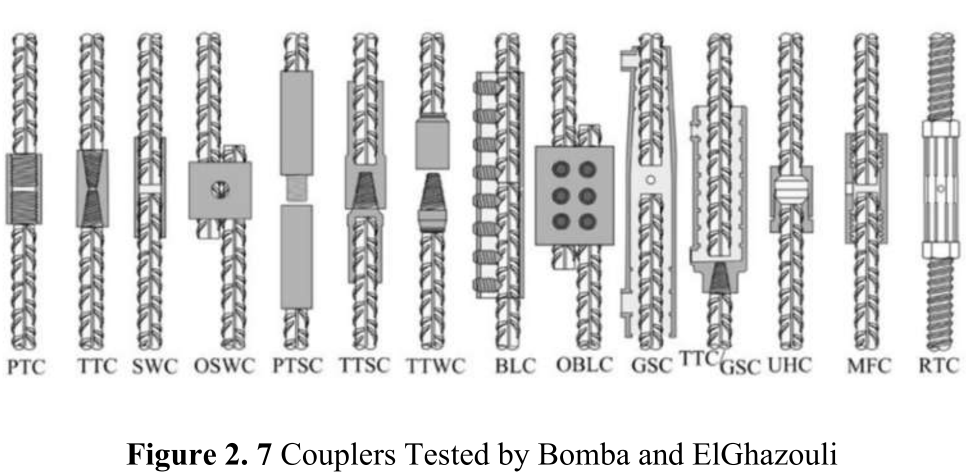


Figure 2. 7 Couplers Tested by Bomba and ElGhazouli

Figure 2.8 displays the test result with the corelation between the strength, ductility and bar size. They concluded, that the ductility was reduced significantly when the bar when the bars were splices using mechanical coupler, and the strain was almost 50% lower compare to the control specimen (unspliced).

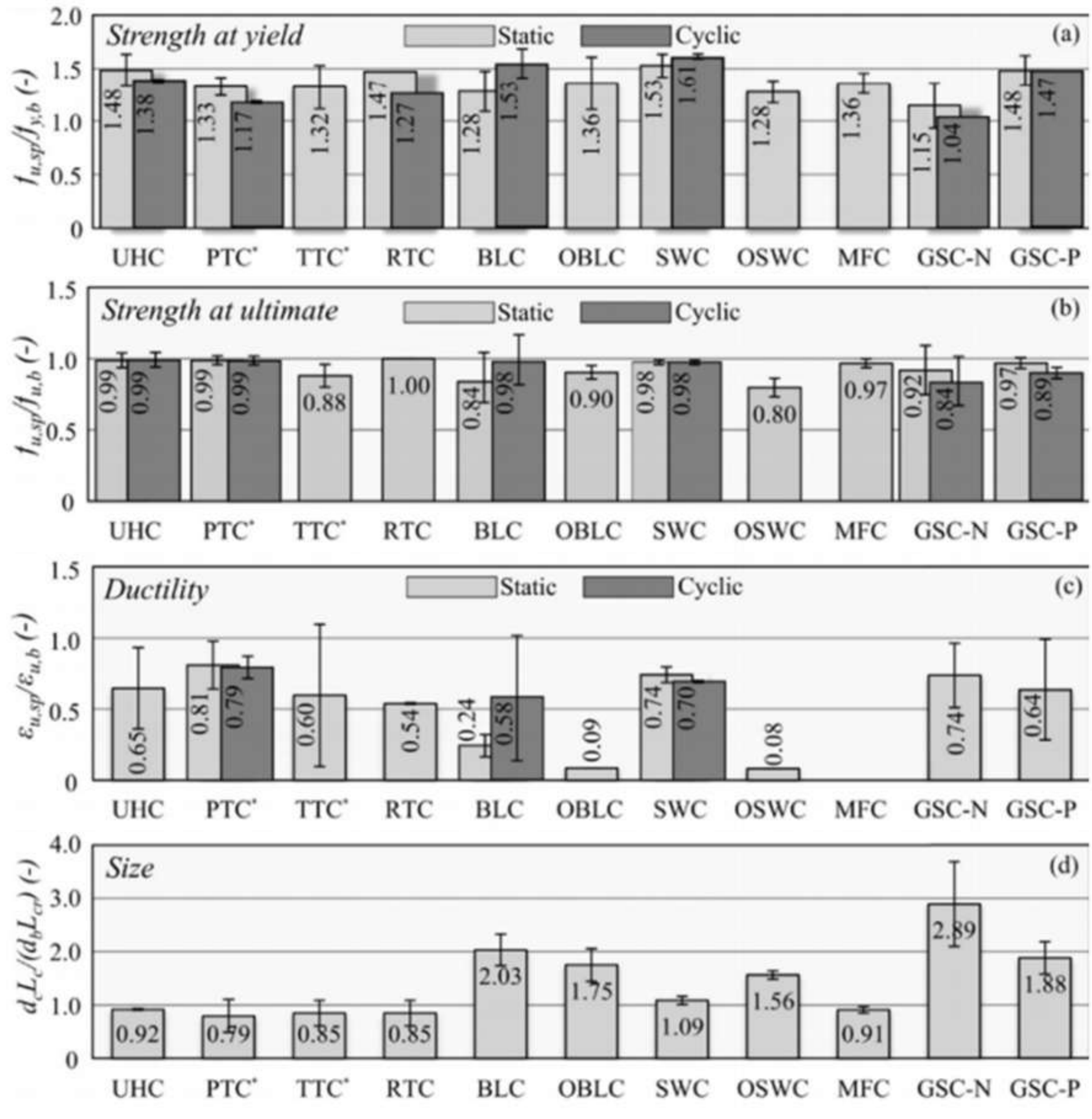


Figure 2. 8 Mechanical Splices Performance by Bompa and ElGhazouli

3. Experimental Program

To study the effect and the influence of the Sleeve mechanical splices on the behavior of the concrete members, twenty-six specimens in total will be fabricated and examined. The specimens were divided in to two phases, The first phase will be the coupler selection phase and it will consist of seventeen specimens that will be tested in a progressive sequence; aiming to narrow the coupler shape, length and installation condition.

This phase will test the couplers bare (rebar and coupler only with no concrete); so, we can inspect how it will perform under compression and how the specimen will fail. Next, the second phase of testing will consist of nine specimens, where we will take the chosen coupler from the previse phase of tests and utilize it in a real-world application, we will use the coupler to connect between the two halves of the main reinforcement for the concrete specimens then test it to failure under multiple conditions.

3.1 The First Phase of Testing “Coupler Selection Phase"

In this stage we will compare between the different types of sleeve couplers with various lengths and bolts spacing to find the most suitable one. This phase will persist in progressive sequence, and for that we have to divide this phase into Three groups, and every group will be dependent on its predecessor, therefore we cannot prep all the specimens at once.

The First group will initiate a Datum line of results to compare to later on in the upcoming tests. The test will apply axial compression load on two rebar connected by a coupler with specific length and bolt spacing. The length of the coupler will be assumed to be 20 cm, and the bolt spacing will be assumed to be double the minimum bolt spacing [ECP= 3Φ] [7] and that will result on a spacing equal to 6Φ. The Second group will study the effect of the coupler length by increasing it once and decreasing it in an another. Then in last and The Third group of the first phase, the bolt spacing will be changed and studied. By the end, the most suitable splice mechanism, length and bolts spacing of the coupler should be identified, and later on be utilized in the Second Group.

There are many types of compression couplers that are used worldwide, but not all of them are present in the Egyptian market. This thesis will focus on three of them that are common globally and can be fabricated without too much hustle, and then forth coupler will be added, to test a new concept of coupling mechanism. The couplers that will be studied are: the Bolted Flange Coupling Sleeve (figure 3.2), the Bolted Straps Coupling Sleeve (figure 3.3), the Nut Locked Coupler (figure 3.4), and lastly the new coupler concept that will be named “the Worm Drive Coupling Sleeve” (figure 3.5).

Figure 3. 1 Bolted Flange Coupling Sleeve

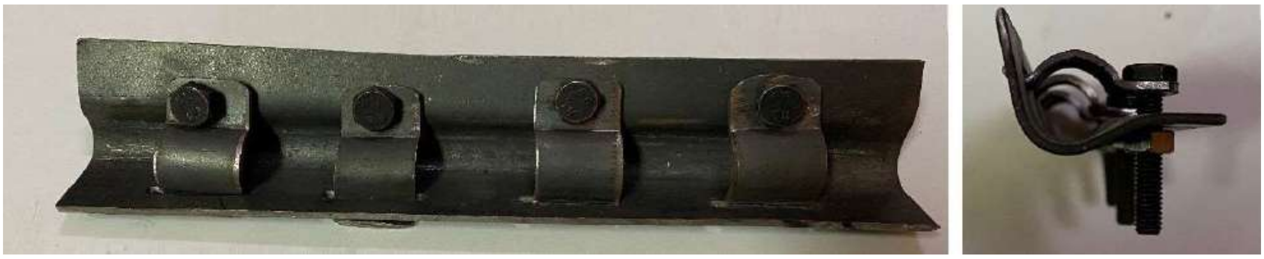


Figure 3. 2 Bolted Straps Coupling Sleeve

Figure 3. 3 Worm Drive Coupling Sleeve

Figure 3. 4 Nut Lock Coupler

Pressing forward, the specimens naming scheme in this group will be as follows:

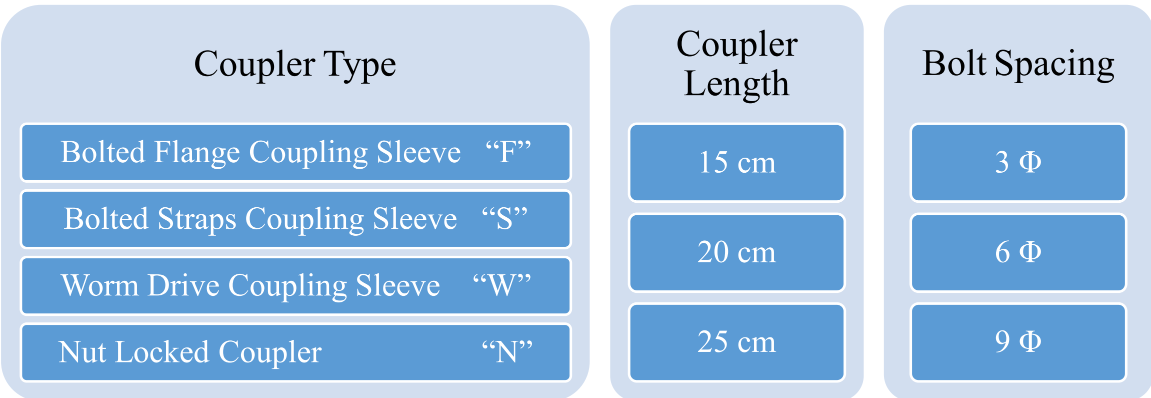


Figure 3. 5 specimens naming scheme

Ex: if a specimen name was (F – 20 - 6 Φ), that is mean that the specimen is a Bolted Flange Coupling Sleeve and it is 20 cm in length with the bolt spacing distance taken 6 times the bolt diameter.

And the specimens schedule will be as follow:

Table 3. 1 Specimens Names and Description

Group Number	Specimen Number	Specimen name	Splice type	Splice length	Bolts spacing
1	Specimen 1	F – 20 - 6 Φ	Bolted Flange Coupling Sleeve	20 cm	4 cm
	Specimen 2	S – 20 - 6 Φ	Bolted Straps Coupling Sleeve	20 cm	4 cm
	Specimen 3	W– 20 - 6 Φ	Worm Drive Coupling Sleeve	20 cm	4 cm
	Specimen 4	N – 20 - 6 Φ	Nut Locked Coupler	20 cm	4 cm
2	Specimen 5	F – 15 - 6 Φ	Bolted Flange Coupling Sleeve	15 cm	4 cm
	Specimen 6	F – 25 - 6 Φ	Bolted Flange Coupling Sleeve	25 cm	4 cm
	Specimen 7	S – 15 - 6 Φ	Bolted Straps Coupling Sleeve	15 cm	4 cm
	Specimen 8	S – 25 - 6 Φ	Bolted Straps Coupling Sleeve	25 cm	4 cm
	Specimen 9	W –15 - 6 Φ	Worm Drive Coupling Sleeve	15 cm	4 cm
	Specimen 10	W –25 - 6 Φ	Worm Drive Coupling Sleeve	25 cm	4 cm
	Specimen 11	N – 15 - 6 Φ	Nut Locked Coupler	15 cm	4 cm
	Specimen 12	N – 25 - 6 Φ	Nut Locked Coupler	25 cm	4 cm
3	Specimen 13	F – 25 - 3 Φ	Bolted Flange Coupling Sleeve	25 cm	2 cm
	Specimen 14	F – 25 - 9 Φ	Bolted Flange Coupling Sleeve	25 cm	6 cm
	Specimen 15	S – 25 - 3 Φ	Bolted Straps Coupling Sleeve	25 cm	2 cm
	Specimen 16	S – 25 - 9 Φ	Bolted Straps Coupling Sleeve	25 cm	6 cm
	Specimen 17	W –25 - 3 Φ	Worm Drive Coupling Sleeve	25 cm	2 cm
	Specimen 18	W –25 - 9 Φ	Worm Drive Coupling Sleeve	25 cm	6 cm
	Specimen19	N – 25 - 3 Φ	Nut Locked Coupler	25 cm	2 cm
	Specimen 20	N – 25 - 9 Φ	Nut Locked Coupler	25 cm	6 cm

3.1.1 Splice Fabrication

In general, the compression mechanical splices consist of a thin steel plate that wraps together the two rebars that mint to be connected and ensure the aligning of their centricity, thus the forces can be transferred between them by end-to-end bearing. Applying sufficient clamping force on the rebars is the main purpose of the splice, and to Achieve it, every splice use's different mechanism.

In this thesis we have study four different splices, three of which ether have been used before, and a one of them will be fabricated for the first time, and they are as follow:

3.1.1.1 Bolted Flange Coupling Sleeve

Figure 3.2. present a sample, it was fabricated from a single sheet of steel with thickness of 2 mm. the edges were pressed in to form a double lip flange for strength, then the sheet was rolled around a smooth rod with a diameter similar to the reinforced rebar, then the flanges were drilled to house a 6 mm bolts (NL 8.8).

Figure 3. 6 Bolted Flange Coupling Sleeve

3.1.1.2 Bolted Straps Coupling Sleeve

This splice as in Figure 3.3 was fabricated from a single sheet of steel with thickness of 2 mm. Four slots were pressed open, so the straps can dig in the flange, then the sheet was Pleated around a rod with a diameter similar to the reinforced rebar, then the other flange was flexed out-word and drilled to house a 6 mm bolts (NL 8.8). the straps were fabricated from the same sheet. They were angled in one end so they can fit in the slots, and drilled in to the other end to be bolted around the rebar to the splice.

Figure 3. 7 Bolted Straps Coupling Sleeve

3.1.1.3 Worm Drive Coupling Sleeve

This one is completely new and (to my knowledge) have never been done before (Figure 3.4). It is a splice that gain it clamping force from a heavy-duty pipe worm clamp that squeeze the steel sheet around the rebar creating the larges contact area between them producing the highest friction. Due to the difficulties of rolling a sheet to this shape, a pipe with a wall thickness of 2 mm and internal diameter similar to the reinforced rebar where used. A longitudinal slot with the length of the splice was cut open; to allow the splice to enfold around the rebar when the worm clamps is tightened.

Figure 3. 8 Worm Drive Coupling Sleeve

3.1.1.4 Nut Locked Coupler

Unlike the previous ones, this splice as in Figure 3.5. is very common and widely used in construction, but we still had to fabricate it; because the off the shelf ones have much thicker side walls and we had to unify the side wall thickness at 2 mm. A pipe with a wall thickness of 2 mm and internal diameter similar to the reinforced rebar were used for this splice, then holes along one side were drilled, due to the thin side walls of the splice; threading these holes to house the bolts were impractical, so threaded nuts were welded on top of it. And like previous splices, the bolt was a 6 mm in diameter (NL 8.8).

Figure 3. 9 Nut Lock Coupler

3.1.2 Test Setup

The test will apply axial compression load on two rebar connected end to end by a coupler. In order to ensure an axial loading, the rebar is welded right angled to a steel plate, the steel plate must be thick enough to resist punching stress and large enough to stay vertically standing till the clamps of the lab machine jaw wedge the sample in. The plate dimension was chosen to be 0.6 cm in thickness, and 10 cm in length and width.

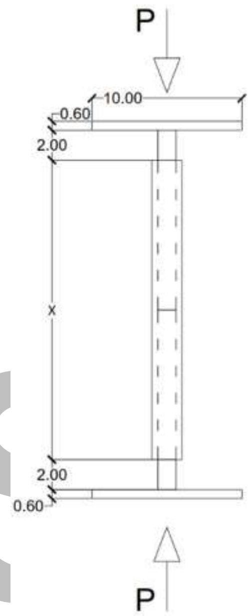


Figure 3. 10 Specimen Setup

3.1.3 Specimens Fabrication

The rebar will be welded in the center of the plate right angled to form a "T" shape in when you look at it from the cross section.

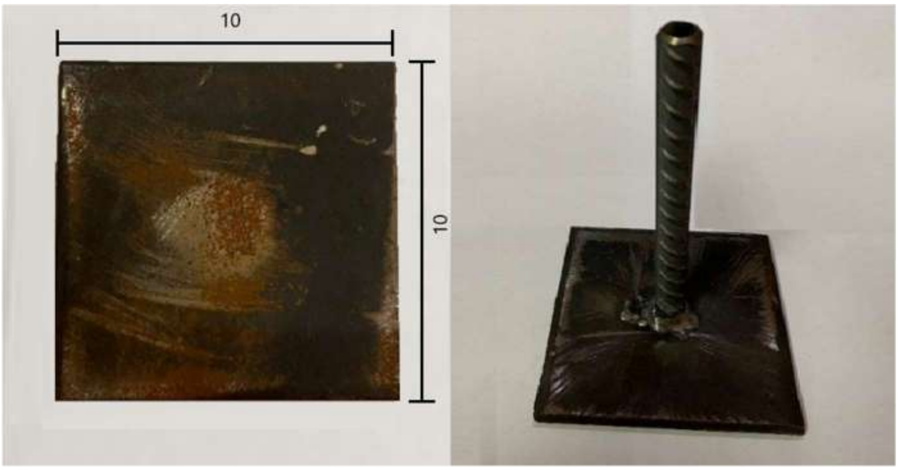


Figure 3. 11 specimens Fabrication

The couplers will connect the two "T" shaped part and form an "I" shaped specimen when you look at it from the side. So, by the end of the fabrication prosses the specimen will consist of a coupler that will connect a two rebars with 12 mm in diameter that are welded right angled in the center of a 10 cm X 10 cm steel plate with 0.6 cm in thickness. And in this order, the rest of specimens in the First Group will be Prepared as shown in figure 3.13.

Figure 3. 12 Specimens Ready for Testing

3.2 First Group of the "Coupler Selection Phase"

In this group we will initiate a Datum line of result to compare to later on the upcoming groups when we start changing the conditions of the specimens. There for, the length and the bolts spacing for the first group will be assumed within reason, taking into consideration the dimensions of a similar mechanism splice, and how easy it is to install the coupler in site. And the selected dimensions are as follows:

- Coupler length will be assumed to be =20 cm.
- Bolt spacing was assumed to be double the minimum bolt spacing. Where, the minimum bolt spacing in the ECP is 3Φ [7] so double it is 6 Φ. The bolt diameter is 0.6 cm, then the distance will equal = 6 x 0.6 = 3.6 cm ≈ 4 cm.

Upon that, the specimens that will be tested in this group are:

1- Specimen No. 1: F – 20 – 6 Φ

2- Specimen No. 2: S – 20 – 6 Φ

3- Specimen No. 3: W– 20 – 6 Φ

4- Specimen No. 4: N – 20 – 6 Φ

3.2.1 Specimen No. 1 (F – 20 – 6 Φ)

Figure 3.14 shows the test setup of (F – 20 - 6 Φ) specimen which uses a Bolted Flange Coupling Sleeve as the way to connect the two rebars, the coupler was 20 cm in length and the bolt spacing was equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so this coupler was fabricated with 4 bolts.

Figure 3. 13 Specimen (F – 20 - 6 Φ) Testing

The specimen was loaded gradually until it started experiencing instability due to high Global buckling in the system along the whole length of the specimen (Figure 3.15). The measured load carrying capacity was 65 kN with a corresponding displacement of 2.55 mm.

Figure 3. 14 Specimen (F – 20 - 6 Φ) Failure Shape

The stress-strain curves for the specimen (F - 20 - 6Φ) was shown in Figure 3.16. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

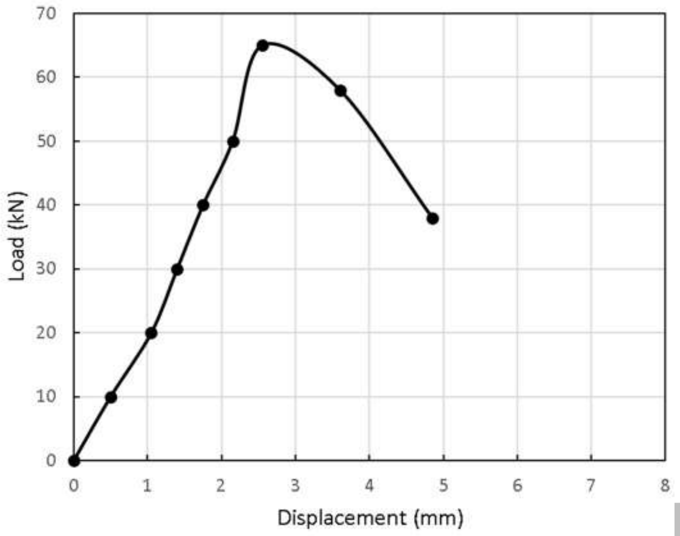


Figure 3. 15 Specimen (F – 20 - 6 Φ) Stress Strain Curve

3.2.2 Specimen No. 2 (S – 20 – 6Φ)

Figure 3.17 shows the test setup of (S – 20 - 6 Φ) specimen which uses a Bolted Straps Coupling Sleeve to fix the two rebars together, the coupler was 20 cm in length and the strap spacing was equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so this coupler was fabricated with 4 straps.

Figure 3. 16 Specimen (S – 20 - 6 Φ) Testing

The specimen was loaded gradually until it started experiencing instability due to high local buckling strain in one end of the rebar, just after the coupler straps ended. The rebar was separated from the coupler and buckled away in the other direction (Figure 3.18). The measured load carrying capacity was 59 kN with a corresponding displacement of 2.45 mm.

Figure 3. 17 Specimen (S – 20 - 6 Φ) Failure Shape

The stress-strain curves for the specimen (S - 20 - 6Φ) was shown in Figure 3.19. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

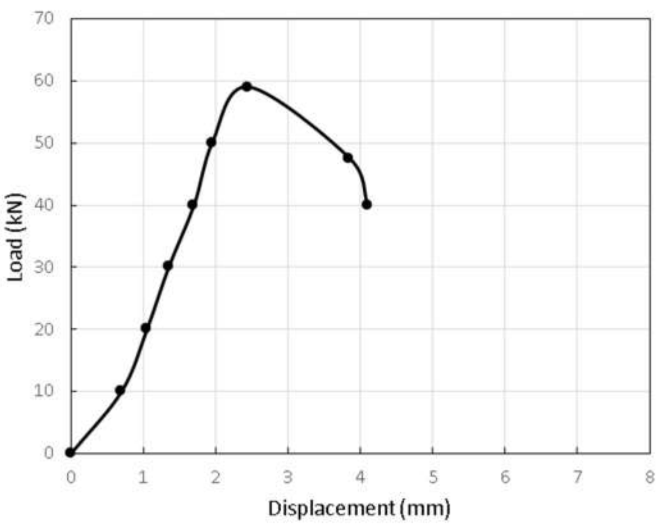


Figure 3. 18 Specimen (S – 20 - 6 Φ) Stress Strain Curve

3.2.3 Specimen No. 3 (W – 20 – 6 Φ)

Figure 3.20 shows the test setup of (W – 20 - 6 Φ) specimen which uses a Worm Drive Coupling Sleeve to connect the two rebars together, the coupler was 20 cm in length and the worm clamps spacing was equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so this coupler was fabricated with 4 clamps.

Figure 3. 19 Specimen (W – 20 - 6 Φ) Testing

The specimen was loaded gradually until it started experiencing instability due to high Global buckling in the system along the whole length of the specimen and a local buckling in the free end of the sleeve flanges (Figure 3.21). The measured load carrying capacity was 58 kN with a corresponding displacement of 2.70 mm.

Figure 3. 20 Specimen (W – 20 - 6 Φ) Failure Shape

The stress-strain curves for the specimen (W - 20 - 6Φ) was shown in Figure 3.22. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

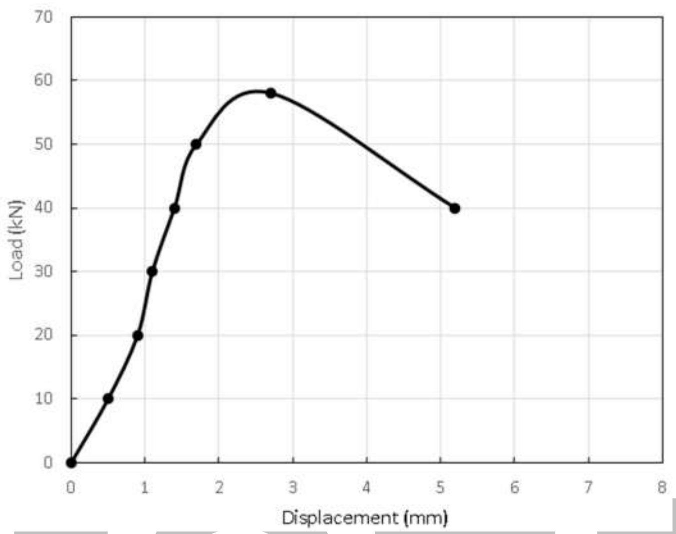


Figure 3. 21 Specimen (W – 20 - 6 Φ) Stress Strain Curve

3.2.4 Specimen No. 4 (N – 20 – 6Φ)

Figure 3.23 shows the test setup of (N – 20 - 6 Φ) specimen which uses a Nut Locked Coupler to fix the two rebars together. The coupler was 20 cm in length and the bolts spacing was equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so this coupler was fabricated with 4 bolts.

Figure 3. 22 Specimen (N – 20 - 6 Φ) Testing

The specimen was loaded gradually until it started experiencing instability due to high local buckling strain in the middle of the coupler where the two rebars were connected, the rebars remained straight throughout the whole loading process (Figure 3.18). The measured load carrying capacity was 59 kN with a corresponding displacement of 4.20 mm.

Figure 3. 23 Specimen (N – 20 - 6 Φ) Failure Shape

The stress-strain curves for the specimen (N - 20 - 6Φ) was shown in Figure 3.25. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

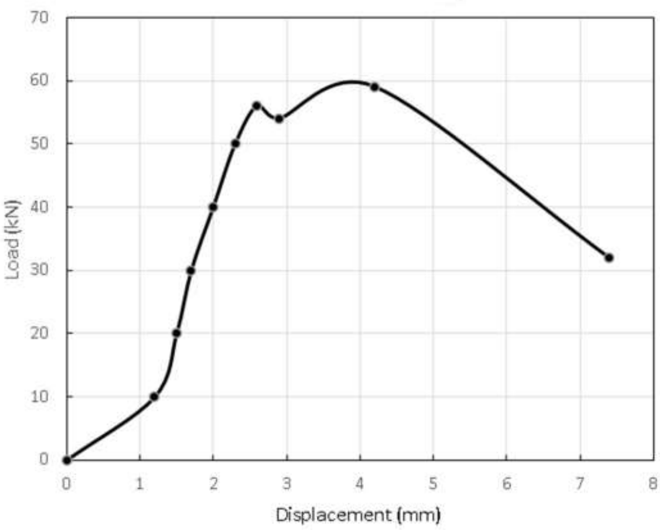


Figure 3. 24 Specimen (N – 20 - 6 Φ) Stress Strain Curve

3.2.5 Comparison Between the First Group Tests Results

After finishing the First Group of tests, some verdicts have been drawn comparing the tests results (Table 3.2).

In terms of Failure load, the Bolted Flange Coupling Sleeve archived the highest Failure load from its competitors by at least 10%. And for the Mode of Failure, the Bolted Flange Coupling Sleeve and The Worm Drive Coupling Sleeve had the closest behavior similar to a plain bar, where the global buckling was distributed evenly on the hole specimen. Both of The Bolted Straps Coupling Sleeve and the Nut Locked Coupler suffered from a local buckling.

The Bolted Straps Coupling Sleeve local buckling occurred in the exposed part of the rebar after the last strap, and that is highlight a disadvantage special for this splice mechanism; and it is that the supported length of the rebar by the coupler is not equal to the coupler length but rather is the distance between the first and the last fixing straps. And for the Nut Locked Coupler, the local buckling occurred in the splice only in the opposite direction of the bolts and the rebar did not suffer any deformation, and that's emphasis a condition special for this type of splice, which is having the biggest eccentricity between the rebar and the coupler from all other types.

Table 3. 2 First Group Tests Results

Spec. no.	Specimen name	Failure Load (kN)	Disp. At Failure (mm)	Mode of Failure
1	F – 20 – 6 Φ	65	2.55	Global buckling Distributed on the hole specimen
2	S – 20 – 6 Φ	59	2.45	Local buckling in the rebar after the last splice strand
3	W– 20 – 6 Φ	58	2.7	Global buckling in the direction of the splice open slot
4	N – 20 – 6 Φ	59	4.2	Local buckling in the splice opposite side to the bolts

The new splice prototype "The Worm Drive Coupling Sleeve" have showed a very promising results, where it's scored almost equal to Both of The Bolted Straps Coupling Sleeve and the Nut Locked Coupler in terms of the load of failure, and behaved at failure similar to normal bar, not mentioning that it was the easiest and cheapest to fabricate.

The Bolted Flanges Coupling Sleeve (F-20-6Φ) was the best performing coupler overall. It managed to archive the highest failure load while maintaining a predictable and gradual mode of failure, distinguishing it from the rest.

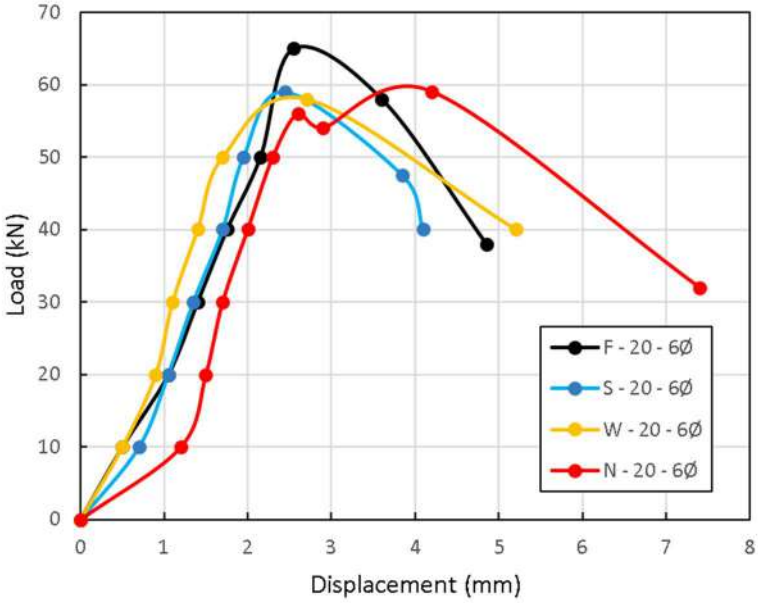


Figure 3. 25 First Group Tests Comparison

3.3 The Second Group of the "Coupler Selection Phase"

After Initiating a datum line of results in the previous group, in this group, one parameter in the coupler dimensions will be changed, and the tests will be run again. Afterward, the results from this group and the previous one will be compared. This group will study the coupler length and it is effect on the specimen load carrying capacity. The length of the coupler will be increased from the previously assumed length in the First group in one specimen, then in another one, the length of the coupler will be decreased. The first group coupler length was assumed to be 20 cm. In this group, the length will be increased by 5 cm to be 25 cm for one specimen, and for the other one, the length will be decreased by 5 cm to be 15 cm. The test will be runed without changing any other parameter, so, the bolt spacing will be maintained at 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm) for all specimens in this group.

Upon that, the specimens that will be tested in this group are:

1- Specimen No. 5: F – 15 – 6 Φ and Specimen No. 6: F – 25 – 6 Φ

2- Specimen No. 7: S – 15 – 6 Φ and Specimen No. 8: S – 25 – 6 Φ

3- Specimen No. 9: W – 15 – 6 Φ and Specimen No.10: W – 25 – 6 Φ

4- Specimen No.11: N – 15 – 6 Φ and Specimen No. 12: N – 25 – 6 Φ

3.3.1 Specimen No. 5 (F – 15 – 6 Φ), Specimen No. 6 (F – 25 – 6 Φ)

Figure 3.27 shows the test setup of (F – 15 – 6 Φ) specimen, and (F – 25 – 6 Φ) specimen, which both of them uses a Bolted Flange Coupling Sleeve as the way to connect the two rebars. Specimen (F – 15 – 6 Φ) was 15 cm in length and specimen (F – 25 – 6 Φ) was 25 cm in length. Both of them had a bolt spacing equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so, the short one was fabricated with 3 bolts, and the long one was fabricated with 5 bolts.

Figure 3. 26 Specimen (F – 15 - 6 Φ), (F – 25 - 6 Φ) Testing

Both specimens were loaded gradually until the specimen started experiencing instability due to: high local buckling strain in one end of the rebar, just after the last bolt for the specimen with the short coupler, and due to high global buckling in the system along the whole length of the specimen with the long coupler (Figure 3.28). The measured load carrying capacity was 66 kN and 71 kN respectively, with a corresponding displacement of 5.30 mm and 4.40 mm.

Figure 3. 27 Specimen (F – 15 - 6 Φ), (F – 25 - 6 Φ) Fail Shape

The stress-strain curves for the specimen (F – 15 – 6Φ) and (F – 25 – 6Φ) was shown in Figure 3.29. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

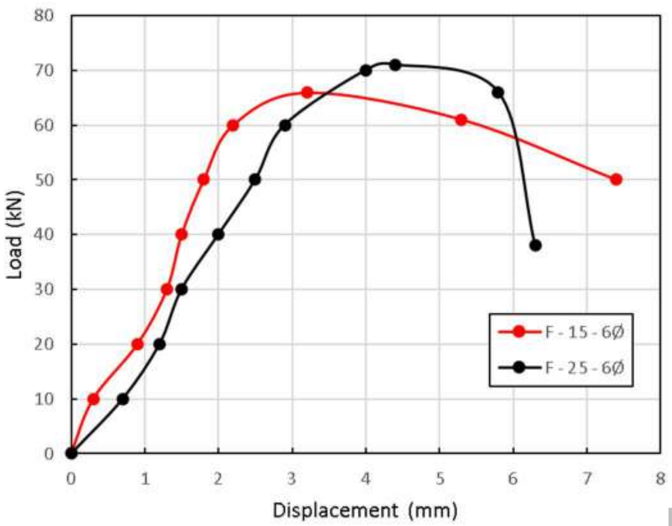


Figure 3. 28 Specimen (F – 15 - 6 Φ), (F – 25 - 6 Φ) Stress Strain Curve

Discussion of Bolted Flange Coupling Sleeve different lengths

The previous tests show that the Bolted Flange Coupling Sleeve benefits from the increased length (Figure 3.30). Where, the Failure Load has increased by almost 10 % when the coupler length had been increased, and the mode of Failure for the longer coupler was a global buckling in the system which is more favorable failure mode than the local buckling of the shorter coupler. Therefore, as predicted, the coupler with a length of 25 cm was the best performer of the bunch.

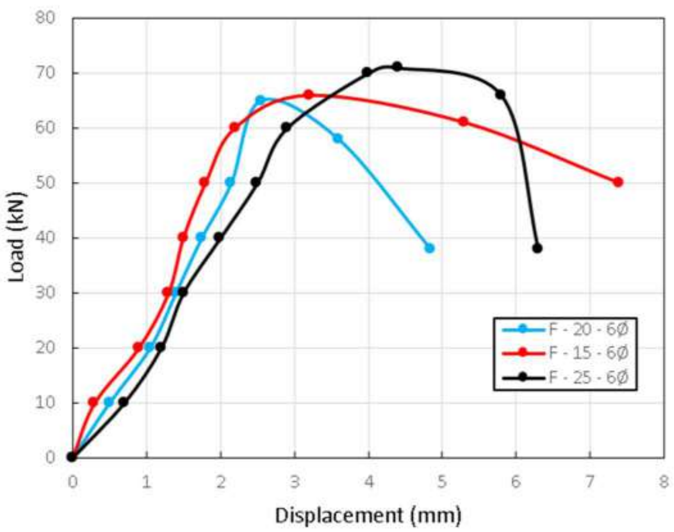


Figure 3. 29 Specimens (F – Var. – 6 Φ) Stress Strain Curve

3.3.2 Specimen No. 7 (S – 15 – 6 Φ), Specimen No. 8 (S – 25 – 6 Φ)

Figure 3.31 shows the test setup of (S – 15 – 6 Φ) specimen, and (S – 25 – 6 Φ) specimen, which both of them uses a Bolted Straps Coupling Sleeve as the way to connect the two rebars. Specimen (S – 15 – 6 Φ) was 15 cm in length and specimen (S – 25 – 6 Φ) was 25 cm in length. Both of them had a strap spacing equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so, the short one was fabricated with 3 straps, and the long one was fabricated with 5 straps.

Figure 3. 30 Specimen (S – 15 - 6 Φ), (S – 25 - 6 Φ) Testing

Both specimens were loaded gradually until the specimen started experiencing instability due to high global buckling in the system along the whole length for both specimens, taking into consideration that the short specimen had an additional local buckling in the sleeve itself (Figure 3.32). The measured load carrying capacity was 61 kN and 62 kN respectively, with a corresponding displacement of 2.70 mm and 2.20 mm.

Figure 3. 31 Specimen (S – 15 - 6 Φ), (S – 25 - 6 Φ) Fail Shape

The stress-strain curves for the specimen (F – 15 – 6Φ) and (F – 25 – 6Φ) was shown in Figure 3.33. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

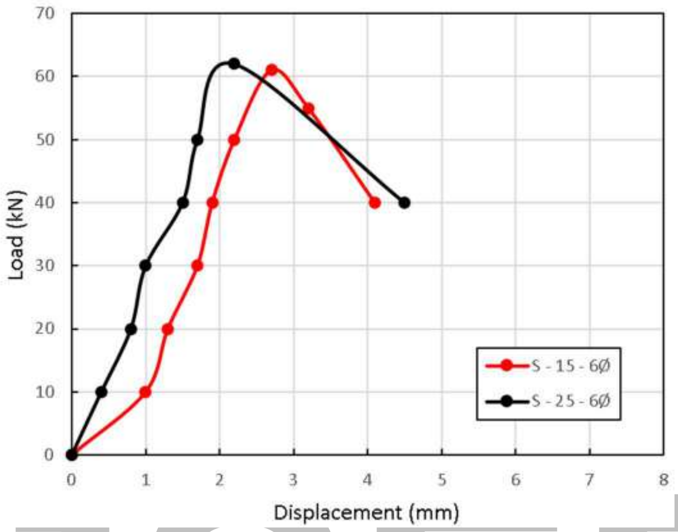


Figure 3. 32 Specimen (S – 15 - 6 Φ), (S – 25 - 6 Φ) Stress Strain Curve

Discussion of Bolted Straps Coupling Sleeve different lengths

The previous tests show that the Bolted Straps Coupling Sleeve does not benefits from the increased length (Figure 3.34). Where, the Failure Load for all specimens with various lengths are almost the same. And for the mode of Failure, the longer coupler and the shorter coupler failed due to a global buckling in the system which is more favorable failure mode, where, the specimen with the medium length coupler failed due to local buckling; that is indicate that the failure mode is not affected by the specimen length. Therefore, this type of coupler mechanism has no optimum length, but for tensile safety purposes; the longer coupler will be chosen.

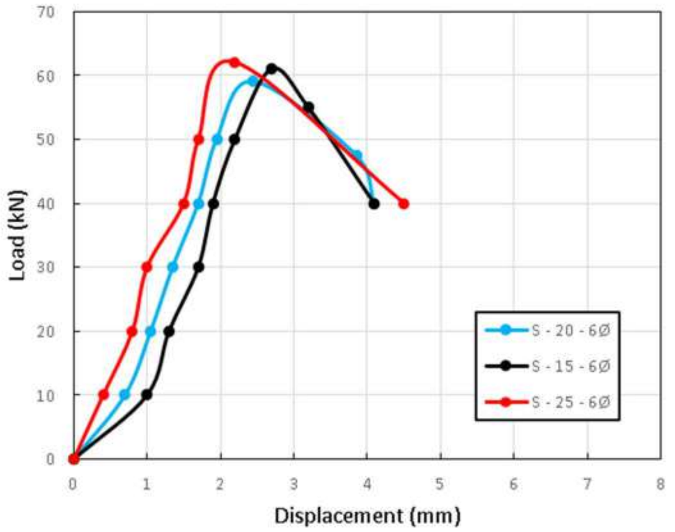


Figure 3. 33 Specimens (S – Var. – 6 Φ) Stress Strain Curve

3.3.3 Specimen No. 9 (W – 15 – 6 Φ), Specimen No. 10 (W – 25 – 6 Φ)

Figure 3.35 shows the test setup of (W – 15 – 6 Φ) specimen, and (W – 25 – 6 Φ) specimen, where both of them uses a Worm Drive Coupling Sleeve, which is a new coupler concept. Specimen (W – 15 – 6 Φ) was 15 cm in length and specimen (W – 25 – 6 Φ) was 25 cm in length. Both of them had a clamp spacing equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so, the short one was fabricated with 3 clamps, and the long one was fabricated with 5 clamps.

Figure 3. 34 Specimen (W – 15 - 6 Φ), (W – 25 - 6 Φ) Testing

The specimens were loaded gradually until they started experiencing instability due to high global buckling in the system along the whole length of the specimen for both of them (Figure 3.36). The measured load carrying capacity was 67 kN and 57 kN respectively, with a corresponding displacement of 4.80 mm and 4.30 mm.

Figure 3. 35 Specimen (W – 15 - 6 Φ), (W – 25 - 6 Φ) Fail Shape

The stress-strain curves for the specimen (W – 15 – 6Φ) and (W – 25 – 6Φ) was shown in Figure 3.37. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

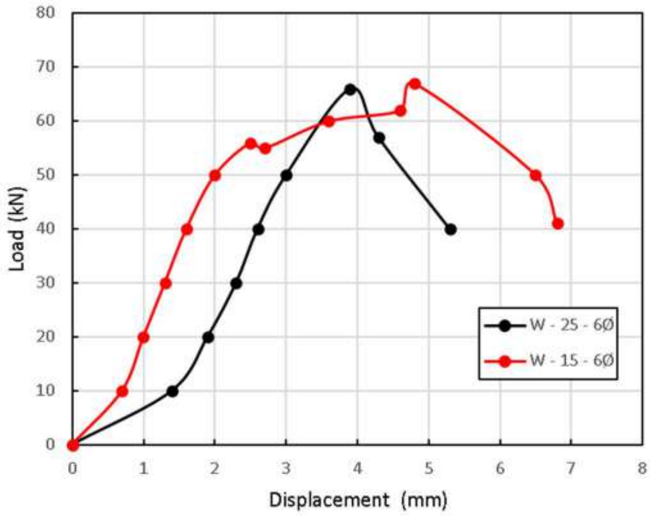


Figure 3. 36 Specimen (W – 15 - 6 Φ), (W – 25 - 6 Φ) Stress Strain Curve

Discussion of Worm Drive Coupling Sleeve different lengths

The previous tests show that the Worm Drive Coupling Sleeve does not benefits from the increased length (Figure 3.38). Where, the Failure Load for all specimens with various lengths were almost the same. And for the mode of Failure, the changing of the coupler length did not change it, which was a global buckling in the system which is more favorable failure mode. Therefore, this type of coupler mechanism is not affected by the coupler length rather by the coupler side wall thickness, but for tensile safety purposes; the longer coupler will be chosen while maintaining the same side wall thickness.

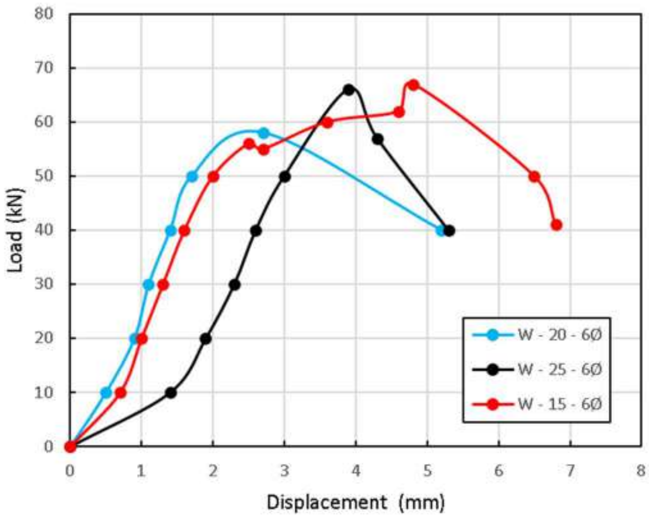


Figure 3. 37 Specimens (W – Var. – 6 Φ) Stress Strain Curve

3.3.4 Specimen No. 11 (N – 15 – 6 Φ), Specimen No. 12 (N – 25 – 6 Φ)

Figure 3.39 shows the test setup of (N – 15 – 6 Φ) specimen, and (N – 25 – 6 Φ) specimen, which both of them uses a Nut Lock Coupler as the way to connect the two rebars. Specimen (N – 15 – 6 Φ) was 15 cm in length and specimen (N – 25 – 6 Φ) was 25 cm in length. Both of them had a bolt spacing equal to 6 Φ (6 x 0.6 = 3.6 cm ≈ 4 cm), so, the short one was fabricated with 3 bolts, and the long one was fabricated with 5 bolts.

Figure 3. 38 Specimen (N – 15 - 6 Φ), (N – 25 - 6 Φ) Testing

The specimens were loaded gradually until they started experiencing instability due to high global buckling in the system along the whole length of the specimen for both of them (Figure 3.36). It can be noted that the failure happed in the opposite side of the bolts no matter what was the coupler length. The measured load carrying capacity was 62.5 kN and 53 kN respectively, with a corresponding displacement of 4.80 mm and 2.90 mm.

Figure 3. 39 Specimen (N – 15 - 6 Φ), (N – 25 - 6 Φ) Fail Shape

The stress-strain curves for the specimen (N – 15 – 6Φ) and (N – 25 – 6Φ) was shown in Figure 3.41. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

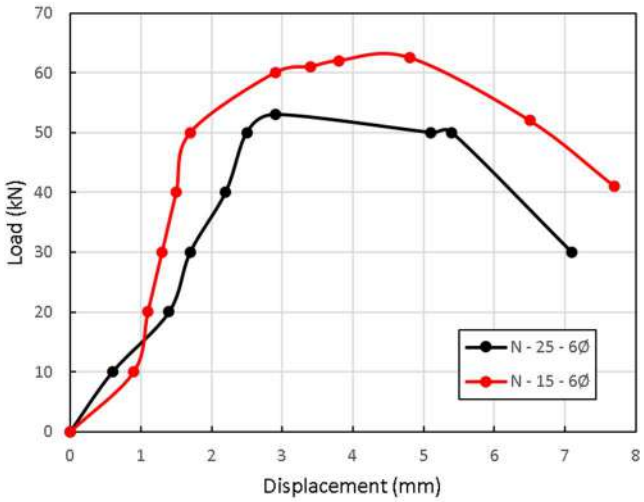


Figure 3. 40 Specimen (N – 15 - 6 Φ), (N – 25 - 6 Φ) Stress Strain Curve

Discussion of Nut Locked Coupler different lengths

The previous tests show that the Nut locked Coupler is hinder by the increased length (Figure 3.42). Where, the Failure Load has decreased by almost 15 % when the coupler length had been increased. And for the mode of Failure, the longer coupler and the shorter coupler failed due to a global buckling in the system which is more favorable failure mode, where, the specimen with the medium length coupler failed due to local buckling; that is indicate that the failure mode is not affected by the specimen length. Therefore, this type of coupler mechanism is not affected by the coupler length rather by the coupler side wall thickness, but for tensile safety purposes; the longer coupler will be chosen.

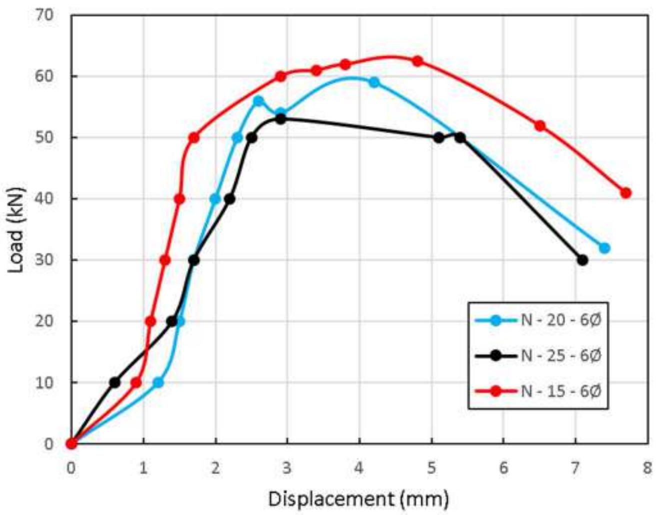


Figure 3. 41 Specimens (N – Var. – 6 Φ) Stress Strain Curve

3.3.5 Comparison Between the Second Group Tests Results

After finishing the Second Group of tests, some verdicts have been drawn comparing the tests results (Table 3.3).

In terms of Failure load, the Bolted Flange Coupling Sleeve specimens managed again to achieve the highest average Failure load from its competitors. Moreover, the added length proved to be beneficial, where it increased the load carrying capacity ever so slightly. And for the Mode of Failure, the Bolted Flange Coupling Sleeve with the longer length failure was due to high global buckling in the system. In contrast, the shorter length did not fare well in the test, where it failed due to local buckling in the coupler flange just after the last bolt. For the rest, the Worm Drive Coupling Sleeve (short and long), the Bolted Straps Coupling Sleeve (short and long) and the Nut Locked Coupler (short and long) all managed to achieve a more favorable failure mode, where they failed due to a global buckling that was distributed evenly along the hole specimen.

Acknowledging that the Bolted Straps Coupling Sleeve had failed due to global buckling, the coupler itself deformed in a way that highlights a disadvantage special for this type of splice mechanism; and it’s that the slots that had to be lasered out of the coupler side wall for the straps to lock in, might cause the deformation of a weak section as seen in figure 3.32, and this is more critical when the slot is in the middle of the coupler as in specimen (S – 15 – 6 Φ).

Table 3. 3 Second Group Tests Results

Spec. no.	Specimen name	Failure Load (kN)	Disp. At Failure (mm)	Mode of Failure
5	F – 15 – 6 Φ	66	5.30	Local buckling
6	F – 25 – 6 Φ	71	4.40	Global buckling
7	S – 15 – 6 Φ	61	2.70	Global buckling
8	S – 25 – 6 Φ	62	2.20	Global buckling
9	W– 15 – 6 Φ	67	4.80	Global buckling
10	W– 25 – 6 Φ	57	4.30	Global buckling
11	N – 15 – 6 Φ	62.5	4.80	Global buckling
12	N – 25 – 6 Φ	53	2.90	Global buckling

Both the Nut Locked Coupler specimen and the new splice type "the Worm Drive Coupling Sleeve" performance have been hindered by the increased length (Figure 3.43). In the case of the Nut Locked coupler, the failure always happening in the opposite side of the bolts, that's again emphasis a condition special for this type of splice mechanism, which is having a big eccentricity between the rebar center and the coupler center. On the other hand, the Worm Drive Coupling Sleeve behavior was the closest to a behavior of a normal plain bar than all of the other couplers, which might be the reason behind the decreased performance to the increased length. Where, in the case of the other couplers, the moment of inertia of the specimen have increased due to the geometric shape of the coupler, contrarily, the Worm Drive Coupling Sleeve almost does not. So, when the specimen length increased, the effective buckling length also increased, which will negatively affect the load carrying capacity for the specimen.

In general, the increased splice length did not have a meaningful impact on the load carrying capacity. Nevertheless, it managed to improve the Mode of Failure greatly all across the board. Where with no exceptions, all the specimens failed due to high global buckling in the system along the whole length of the specimen, without a single case of local buckling.

The Bolted Flanges Coupling Sleeve (F – 25 – 6Φ) was the best performing coupler overall in the second group (Figure 3.43). It managed to archive the highest average failure load while maintaining a predictable and gradual mode of failure. However, it has to be noted, that decreasing the distance between the last bolt and the end of the coupler might have a positive effect on the behavior, which was deduced from the behavior of its shorter brother specimen (F – 15 – 6Φ) (figure 3.28).

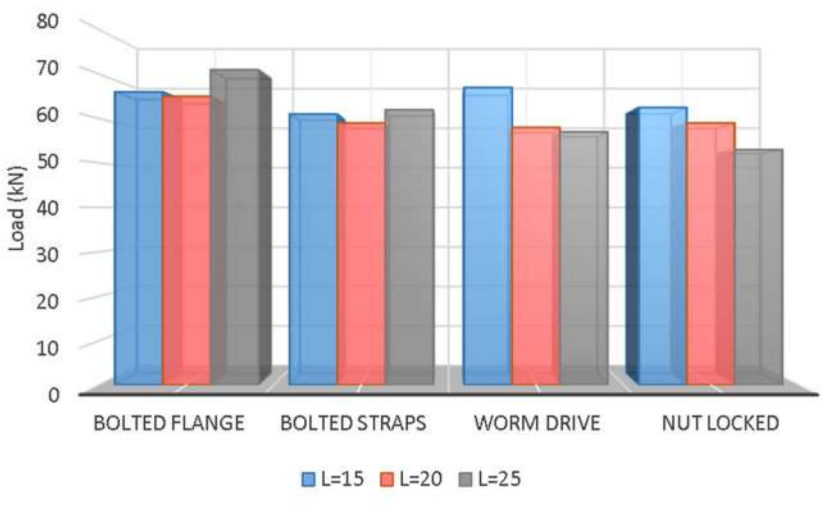


Figure 3. 42 First and Second Group Tests Result Comparison

3.4 The Third Group of the "Coupler Selection Phase"

The previous groups have tested initially the feasibility of using this type of couplers. Then, the group after studied the effect of changing the assumed length of the coupler on the specimen performance. The previous tests have proved that the increased length have affected both of the load carrying capacity and the mode of failure positively. Continuing the same approach, in this group, one parameter in the coupler dimensions will be changed, and the tests will be run again. Afterward, the results from this group and the previous ones will be compared.

This group will study the couplers bolts (or fixings) spacing and it is effect on the specimen load carrying capacity. The spacing of the bolts (or fixings) will be increased from the previously assumed one in the First group for one specimen, then in another one, the spacing will be decreased. The first and the second group of couplers spacing was assumed to be 6 Φ. In this group, the spacing will be increased to be 9 Φ (9 x 0.6 = 5.4 cm ≈ 6 cm) for one specimen, and for the other one, the spacing will be decreased to be 3 Φ (3 x 0.6 = 1.8 cm ≈ 2 cm), and this will mean, the spacing will have been studied at 2,4 and 6 cm. The test will be run without changing any other parameter. So, the coupler length will be maintained at 25 cm (deduced from the second group) for all specimens in this group.

Upon that, the specimens that will be tested in this group are:

1- Specimen No. 13: F – 25 – 3 Φ and Specimen No. 14: F – 25 – 9 Φ

2- Specimen No. 15: S – 25 – 3 Φ and Specimen No. 16: S – 25 – 9 Φ

3- Specimen No. 17: W – 25 – 3 Φ and Specimen No. 18: W – 25 – 9 Φ

4- Specimen No.19: N – 25 – 3 Φ and Specimen No. 20: N – 25 – 9 Φ

And by the end of this group, every aspect of the coupler properties has been tested and analyzed. Were, the coupler mechanism was studied in the first group. Then, the coupler length had been tested in the second group. And finally, the fixing spacing will be studied in this one. And this will mark the end of the first phase.

3.4.1 Specimen No. 13 (F – 25 – 3 Φ), Specimen No. 14 (F – 25 – 9 Φ)

Figure 3.44 shows the test setup of (F – 25 – 3 Φ) specimen, and (F – 25 – 9 Φ) specimen, which both of them uses a Bolted Flange Coupling Sleeve as the way to connect the two rebars. Both Specimens were 25 cm in length. Specimen (F – 25 – 3 Φ) spacing was (3 x 0.6 = 1.8 cm ≈ 2 cm), so it had to be fabricated with 9 bolts, but due to difficulties of implementing this for all splices, it will be fabricated with 7 bolts, (F – 25 – 9 Φ) spacing was (9 x 0.6 = 5.4 cm ≈ 6 cm) so it will be fabricated with 4 bolts.

Figure 3. 43 Specimen (F – 25 - 3 Φ), (F – 25 - 9 Φ) Testing

Both specimens were loaded gradually until the specimens started experiencing instability due to high global buckling in the system along the whole length of the specimen, which was the case for both of them (Figure 3.45). The measured load carrying capacity was 62 kN and 59 kN respectively, with a corresponding displacement of 3.10 mm and 3.40 mm.

Figure 3. 44 Specimen (F – 25 - 3 Φ), (F – 25 - 9 Φ) Fail Shape

The stress-strain curves for the specimen (F – 25 – 3Φ) and (F – 25 – 9Φ) was shown in Figure 3.46. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

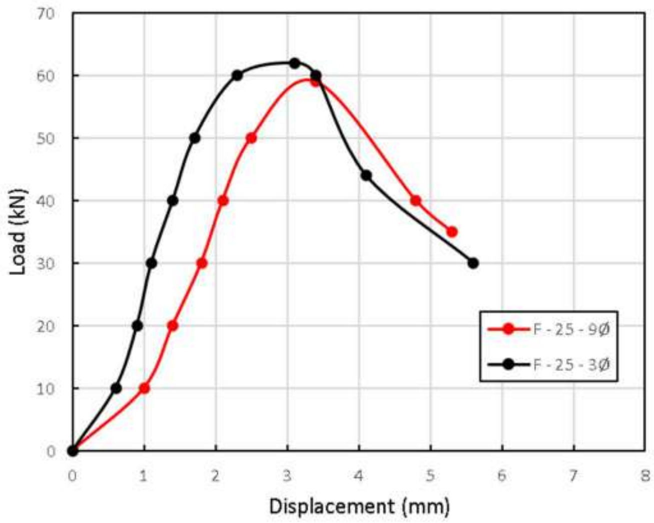


Figure 3. 45 Specimen (F – 25 - 3 Φ), (F – 25 - 9 Φ) Stress Strain Curve

Discussion of Bolted Flange Coupling Sleeve Different Spacing

The previous tests show that the Bolted Flange Coupling Sleeve does not get effected by the change in bolt spacing (Figure 3.47). Where, the Failure Load for all specimens with different spacings are almost the same. And for the mode of Failure, all specimens failed due to a global buckling in the system which is more favorable failure mode. It is concluded that the various bolt spacings were all sufficient enough for this type of coupler. But for ease of installation; the bigger bolt spacing will be chosen.

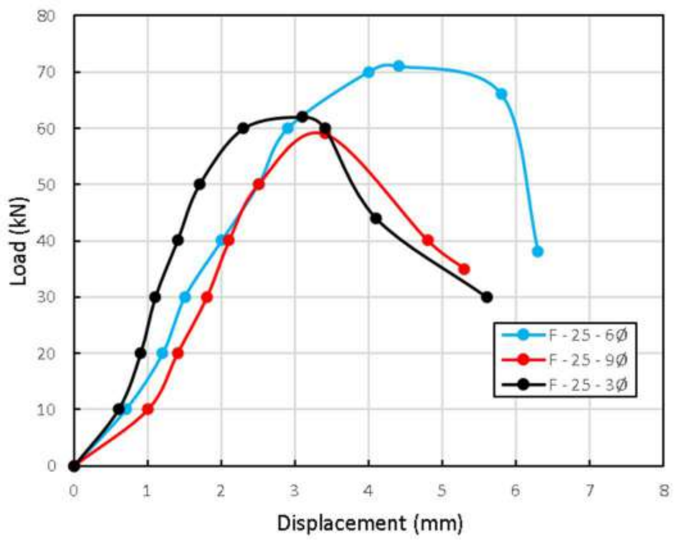


Figure 3. 46 Specimens (F – 25 – Var. Φ) Stress Strain Curve

3.4.2 Specimen No. 15 (S – 25 – 3 Φ), Specimen No. 16 (S – 25 – 9 Φ)

Figure 3.48 shows the test setup of (S – 25 – 9 Φ) specimen which uses a Bolted Straps Coupling Sleeve as the way to connect the two rebars. Due to this type of splice mechanism that need a slot for the straps to snaps on; increasing the number of straps will increase the number of open slots in the coupler sidewall, creating a weak section, therefore, specimen (S – 25 – 3 Φ) will not be fabricated (Figure 3.48). The Specimen (S – 25 – 9 Φ) was 25 cm in length, and the spacing was (9 x 0.6 = 5.4 cm ≈ 6 cm) so it will be fabricated with 4 straps.

Figure 3. 47 Specimen (S – 25 - 3 Φ), (S – 25 - 9 Φ) Testing

The specimen was loaded gradually until it started experiencing instability due to high global buckling in the system along the whole length of the specimen (Figure 3.49). There was no local buckling zone in the coupler or in the bars. The measured load carrying capacity was 61 kN, with a corresponding displacement of 3.90 mm.

Figure 3. 48 Specimen (S – 25 - 9 Φ) Fail Shape

The stress-strain curves for the specimen (F – 25 – 9 Φ) was shown in Figure 3.50. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

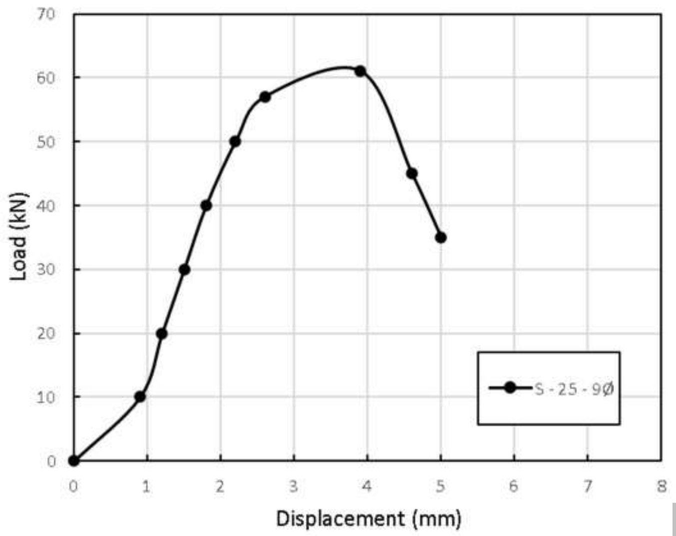


Figure 3. 49 Specimen (S – 25 - 9 Φ) Stress Strain Curve

Discussion of Bolted Straps Coupling Sleeve Different Spacing

The previous tests show that the Bolted Straps Coupling Sleeve is not impacted by the change in strap spacing (Figure 3.51). Where, the Failure Load for all specimens with different spacings are almost the same. And for the mode of Failure, all specimens failed due to a global buckling in the system which is more favorable failure mode. This is affirming that the various straps spacings were all sufficient enough for this type of coupler. But for ease of installation and fabrication; the coupler bigger straps spacing will be chosen.

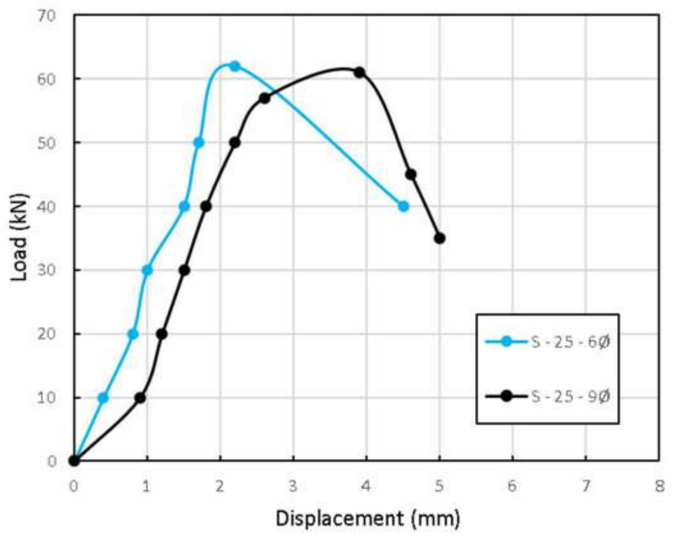


Figure 3. 50 Specimens (S – 25 – Var. Φ) Stress Strain Curve

3.4.3 Specimen No. 17 (W – 25 – 3 Φ), Specimen No. 18 (W – 25 – 9 Φ)

Figure 3.52 shows the test setup of (W – 25 – 3 Φ) specimen, and (W – 25 – 9 Φ) specimen, which both of them uses a Worm Drive Coupling Sleeve, which is a new coupler concept. Both Specimens were 25 cm in length. Specimen (W – 25 – 3 Φ) spacing was (3 x 0.6 = 1.8 cm ≈ 2 cm), so it had to be fabricated with 9 clamps, but due to difficulties of implementing this (Figure 3.52), it will be fabricated with 7. (W – 25 – 9 Φ) spacing was (9 x 0.6 = 5.4 cm ≈ 6 cm) so it will be fabricated with 4 clamps.

Figure 3. 51 Specimen (W – 25 - 3 Φ), (W – 25 - 9 Φ) Testing

The specimens were loaded gradually until they started experiencing instability due to high global buckling in the system along the whole length of the specimen for both of them (Figure 3.53). The measured load carrying capacity was 55 kN and 53 kN respectively, with a corresponding displacement of 3.00 mm and 4.20 mm.

Figure 3. 52 Specimen (W – 25 - 3 Φ), (W – 25 - 9 Φ) Fail Shape

The stress-strain curves for the specimen (W – 25 – 3Φ) and (W – 25 – 9Φ) was shown in Figure 3.54. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

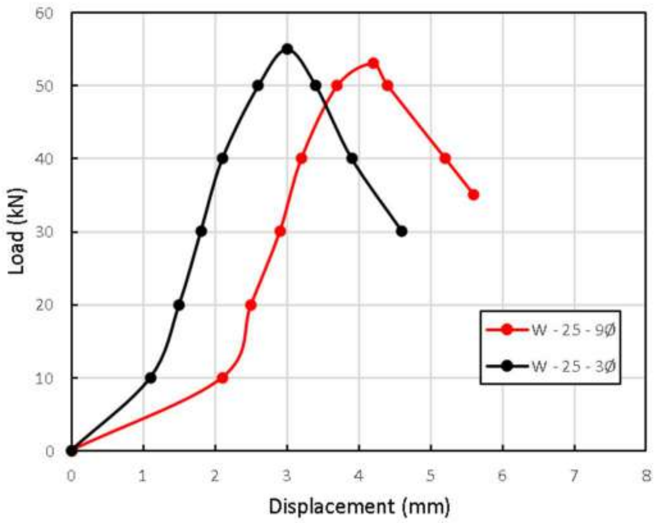


Figure 3. 53 Specimen (W – 25 - 3 Φ), (W – 25 - 9 Φ) Stress Strain Curve

Discussion of Worm Drive Coupling Sleeve Different Spacing

The previous tests show that the Worm Drive Coupling Sleeve is not greatly affected by the change in clamps spacing (Figure 3.55). Where, the Failure Load for all specimens with various spacings are within the margin of error. And for the mode of Failure, all specimens failed due to a global buckling in the system which is more favorable failure mode. This is confirming that the various clamps spacings were all sufficient enough for this type of coupler. Taking in to consideration the local buckling in Figure 3.21, the 6 Φ spacing with a clamp at the middle of the coupler will be chosen.

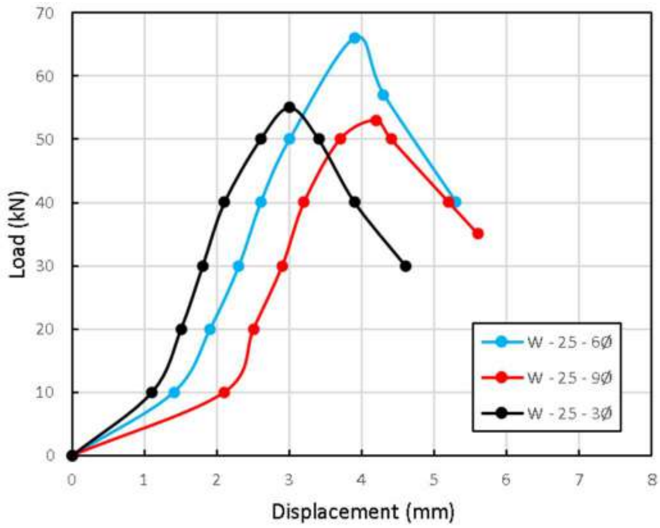


Figure 3. 54 Specimens (W – 25 – Var. Φ) Stress Strain Curve

3.4.4 Specimen No. 19 (N – 25 – 3 Φ), Specimen No. 20 (N – 25 – 9 Φ)

Figure 3.56 shows the test setup of (N – 25 – 3 Φ) specimen, and (N – 25 – 9 Φ) specimen, where both of them uses a Nut Lock Coupler as the way to connect the two rebars. Both Specimens were 25 cm in length. Specimen (N – 25 – 3 Φ) spacing was (3 x 0.6 = 1.8 cm ≈ 2 cm), so it had to be fabricated with 9 bolts, but due to difficulties of implementing this for all specimens, it will be fabricated with 7. The (N – 25 – 9 Φ) spacing was (9 x 0.6 = 5.4 cm ≈ 6 cm) so it will be fabricated with 4 bolts.

Figure 3. 55 Specimen (N – 25 - 3 Φ), (N – 25 - 9 Φ) Testing

Both specimens were loaded gradually until the specimens started experiencing instability due to high global buckling in the system along the whole length of the specimen, which was the case for both specimens (Figure 3.57). The measured load carrying capacity was 65 kN and 69 kN respectively, with a corresponding displacement of 2.80 mm and 4.80 mm.

Figure 3. 56 Specimen (N – 25 - 3 Φ), (N – 25 - 9 Φ) Fail Shape

The stress-strain curves for the specimen (N – 25 – 3 Φ) and (N – 25 – 9 Φ) was shown in Figure 3.58. The curve displays the specimen loading prosses with the corresponding displacement for it with an increment of 10 kN. From the curve, the maximum load carrying capacity, displacement at failure and the specimen stiffness can be specified.

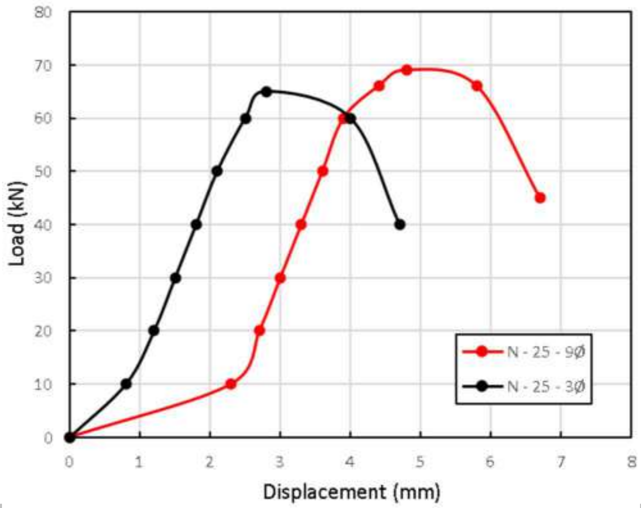


Figure 3. 57 Specimen (N – 25 - 3 Φ), (N – 25 - 9 Φ) Stress Strain Curve

Discussion of Nut Locked Coupler Different Spacing

The previous tests show that the Nut locked Coupler is not greatly hindered by the change in bolts spacing (Figure 3.59). Where, the Failure Load for all specimens with various spacings were inconsistent with expected results due to the changes in the spacing. And for the mode of Failure, all specimens failed due to a global buckling in the system which is more favorable failure mode. Therefore, the bolts spacing will be taken at 3 Φ, where it combines between the adequate load capacity with the intended failure mode, moreover the ease of installation.

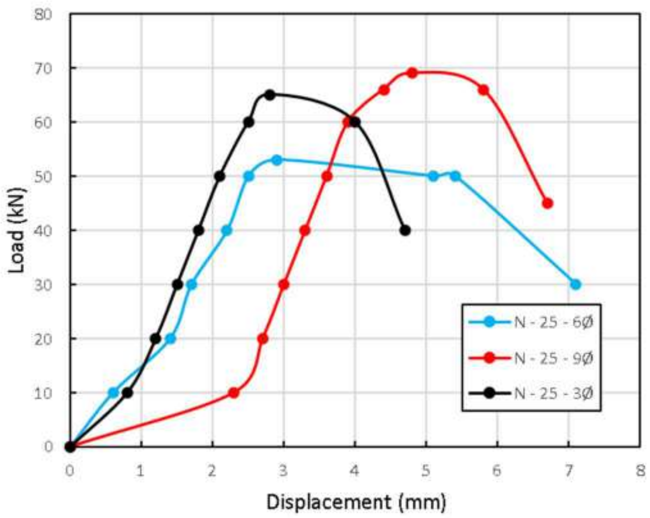


Figure 3. 58 Specimens (N – 25 – Var. Φ) Stress Strain Curve

3.4.5 Comparison Between the Third Group Test Result

After finishing the third and final group of The First Phase, some verdicts have been drawn comparing the tests results (Table 3.4).

In terms of Failure load, unlike the previous groups, increasing or decreasing the previously assumed bolts (or fixings) spacing had no meaningful gains in the overall load carrying capacity for all specimens alike, and there is no distinguish advantage for any type of coupler over the others. And for the Mode of Failure, again, increasing or decreasing the previously assumed bolts (or fixings) spacing had no clear influence on the failure mode. Where, all of the Bolted Flange Coupling Sleeve specimens, the Bolted Straps Coupling Sleeve specimens, the Worm Drive Coupling Sleeve specimens and the Nut Locked Coupler specimens, all managed to achieve a more favorable failure mode, where they all failed due to a global buckling that was distributed evenly along the hole specimen.

The Bolted Straps Coupling Sleeve mechanism prevent it from increasing the straps number for a specific coupler length. Where, increasing the number of straps will accordingly increase the number of slots that have to be opened in the splice sidewall, creating weak section along the slots (Figure 3.48), therefore, specimen (S – 25 – 3 Φ) was not been fabricated. For the (S – 25 – 9 Φ) specimen, it performed exactly just like the (S – 25 – 6 Φ) with a failure load difference less than 2% and with the same mode of failure, affirming that the spacing at 9 Φ was sufficient enough for this coupler type.

Table 3. 4 Third Group Tests Results

Spec. no.	Specimen name	Failure Load (kN)	Disp. At Failure (mm)	Mode of Failure
13	F – 25 – 3 Φ	62	3.10	Global buckling
14	F – 25 – 9 Φ	59	3.40	Global buckling
15	S – 25 – 3 Φ	-	-	-
16	S – 25 – 9 Φ	61	3.90	Global buckling
17	W– 25 – 3 Φ	55	3.00	Global buckling
18	W– 25 – 9 Φ	53	4.20	Global buckling
19	N – 25 – 3 Φ	65	2.80	Global buckling
20	N – 25 – 9 Φ	69	4.80	Global buckling

For the Worm Drive Coupling Sleeve Specimen, increasing or decreasing the spacing between the worm drive clamps had almost no effect on the overall load carrying capacity and on the mode of failure. Whereas, the spacing at 3 Φ, 6 Φ and 9 Φ all proven to be adequate enough for this coupler to be effective and for the specimen as a whole to behave in a manner closer to the behavior of a normal plain bar than all of the other couplers.

The Nut Locked Coupler specimens on the other hand were different than the rest. Where, the results from the third group of tests were inconsistent and does not align with the logical predicted results, this means that there are other factors influencing the result. From rereviewing the specimens, other reasons emerged, and it is about the reliability of the coupler rebar fixing method. The Nut Locked Coupler compared by the rest, have the lowest contact area between the coupler and the rebar, moreover, this coupler always fabricated with a very beefy side walls, fabricating it with a side wall thickness similar to the other coupler seem to hinder it is mechanism to functions right, producing in this case an unreliable connection with un predictable behavior under load. There for this coupler type have been determined not suitable for this use case under these specific circumstances.

In general, changing the bolts (or fixings) spacing within reason seem to have a little to no effect on the coupler load carrying capacity or on the mode of failure. Where, the results from this group are almost the same from the group prior.

The Bolted Flanges Coupling Sleeve (F – 25 – 9Φ) was the best performing coupler overall in the third group (Figure 3.60). It managed to archive the highest failure load while maintaining a predictable and gradual mode of failure. However, it has to be noted that decreasing the distance between the last bolt and the end of the coupler might have a positive effect on the behavior, which was deduced from the behavior of its shorter brother specimen (F – 15 – 6Φ) (figure 3.28).

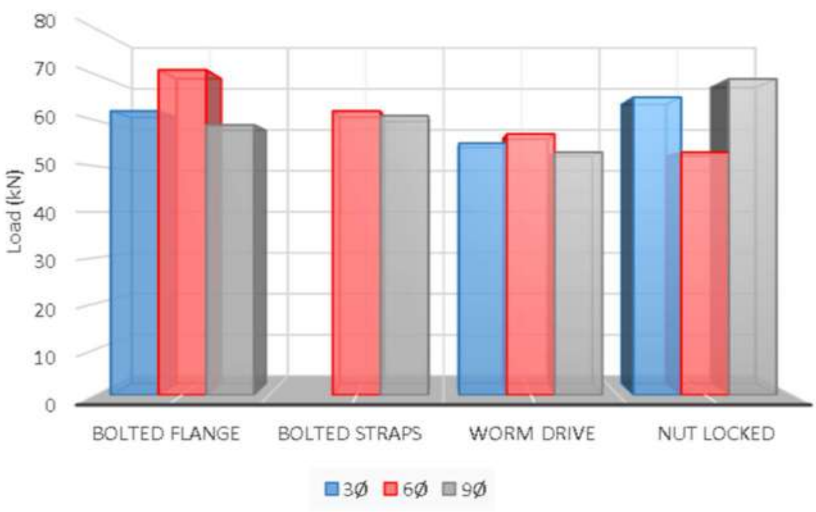


Figure 3. 59 First and Second Group Tests Result Comparison

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