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# Assessing the seismic performance of reinforcement coupler systems

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**ABSTRACT:** International literature reporting on reinforcing mechanical connection system testing protocols and experimental studies conducted in the United States, Japan, and Europe were assessed to provide recommendations for an upcoming review of the New Zealand reinforced concrete design standard. Both static and seismic conditions, in terms of their relevance in the New Zealand context, were considered in the literature review. At conclusion of this exercise, new standard criteria for the use of mechanical connection systems in New Zealand were proposed, and a range of couplers commonly used in New Zealand were subjected to preliminary tests in accordance with the proposed standard criteria. Testing indicated that the couplers performed in a satisfactory manner.

## 1 INTRODUCTION

Use of mechanical connection systems in reinforced concrete has become increasingly prevalent in New Zealand. Mechanical connectors are an alternative to lap and welded splices, and many are capable of developing the full strength of the connected reinforcing bars. There are many advantages for using mechanical connector systems over conventional reinforcing bar lapping. Such examples are overcoming reinforcement congestion problems and convenience when installing precast construction members at sites.

The purpose of this research was to establish the suitability of the current New Zealand reinforced concrete design standard's (NZS 3101: 1995) approach to the performance verification of mechanical connectors. The research was motivated by the facts that the criteria in the current reinforced concrete standard were based on 1977 research, while there has been a substantial advancement in this field worldwide in recent years.

This paper presents:

- Findings on international trends of mechanical connection systems;
- Recommendations for upcoming New Zealand reinforced concrete standard review; and
- Indicative test results using newly adopted testing protocol.

## 2 LITERATURE REVIEW

International literature reporting on mechanical connection testing protocols and experimental studies conducted in the United States, Japan, and Europe were assessed to provide recommendations for upcoming review of the New Zealand reinforced concrete standard. Both static and seismic conditions, in terms of their relevance in the New Zealand context, were examined in this literature review.

## 2.1 **Current New Zealand Requirements**

The current New Zealand reinforced concrete design standard, NZS 3101: 1995, demands strength and stiffness requirements for mechanical connection systems under static conditions:

- The strength of mechanical connectors must be stronger than breaking strength of the spliced reinforcing bars; and
- Elongation occurrence within the mechanical connection system must not exceed that of an equal length of unspliced reinforcing bar under 0.7 $f_y$, in tension and compression.

Under seismic conditions, the code requires an additional stiffness criterion to the two static ones. In order to comply with this, the connection system is to be subjected to a cyclic test. Eight full cycles of 0.95 $f_y$, in both tension and compression, are to be applied. The change of length occurring in the connection system after this cyclic load must be less than 10 percent in excess of the extension in an equal length of unspliced bar. If designers are to use connectors that do not comply with this stiffness criterion, the code recommends such connectors to be staggered so that less than 2/3 reinforcement area is spliced within any 900 mm length of the member.

## 2.2 **World Trend – Static Conditions**

Based on assessment of the international literature, a general conclusion was drawn. For use of mechanical connection systems in static conditions, three categories need to be considered, and they are:

- Strength;
- Serviceability limit state; and
- Fatigue loading.

### 2.2.1 *Strength*

The general trend for strength requirement of mechanical connectors in static conditions is that the strength of the connectors must be larger than that of the spliced reinforcing bars. Most reinforced concrete design standard organisations demand an overstrength factor to be multiplied to the specified yield strength of the spliced reinforcing bars for the connector's strength requirement. This overstrength factor tends to be governed by both safety based on reinforcing bar manufacturer's quality control and on economy considerations. Some organisations are more restrictive than others in this matter, as they require the connector strength to be more than the specified ultimate strength of the spliced reinforcing bars. The basic logic behind the above requirements is that the spliced reinforcing bars must yield and eventually fail before the ultimate failure of mechanical connectors under loading situation, thus avoiding brittle failure of the connectors.

### 2.2.2 *Serviceability Limit State*

A number of reinforced concrete design standards recognise possible concrete cracking, which may arise from slip between the spliced reinforcing bar and the mechanical connector, thus constituting a serviceability limit state. It is understood that this slip, which is a permanent or residual deformation, is a matter of manufacturer's quality control on interlock between the spliced reinforcing bar and the connector. It also is understood that the mechanical connection system tends to be more rigid once it is subjected to low stress. The reason for this is the plastic deformation due to bearing within the interlocked system of the reinforcing bar and the connection.

Serviceability limit state design in reinforced concrete under static conditions is an important aspect that structural engineers need to consider. Appropriate crack width limits provide an aesthetically sound environment for the public as well as preventing possible corrosion occurrence in reinforcing bars.

### 2.2.3 *Fatigue Loading Situation*

A few organisations require fatigue testing of mechanical connection systems. This fatigue loading, which is a high number of cycles within the elastic stress range, can affect the mechanical connector's performance. However, assessing fatigue behaviour of the mechanical connectors was beyond the scope of the research reported here.

## 2.3 **World Trend – Seismic Conditions**

When assessing international literature, special attention was given to the requirements of JCI[1], ISO/CD[1] 15835 (Draft), and ICBO[1] (AC 133). It was found that these three organisations were using a similar loading sequence for testings, shown in the table below, in order to verify performance of mechanical connection systems in seismic conditions.

**Table 1. Common seismic loading application**

| Test Description | Labelling | | Loading Application | | |
|---|---|---|---|---|---|
| | JCI | ISO | Tension | Compression | Cycles |
| A | Elastic Cyclic Test | Medium Scale Simulated EQ Loading | 0.95 $f_y$ | 0.5 $f_y$ | 20 |
| B | Plastic Cyclic Test | Violent Scale Simulated EQ Loading | 2 $\varepsilon_y$ | 0.5 $f_y$ | 4 |
| | | | 5 $\varepsilon_y$ | 0.5 $f_y$ | 4 |

In order to comply with ICBO's AC133, each mechanical connection system specimen must survive the combined loading of A and B from the above table. For both JCI[1] and ISO[1], separate samples must be subjected to each test.

Although these three organisations stipulate the same loading sequence, there were differences, shown in the table below, between the procedure that each organisation adopted to determine the yield strain.

**Table 2. $e_y$ value determination**

| Organisations | Establishing $e_y$ value |
|---|---|
| ICBO (AC133) | Strain of reinforcing bar at actual yield stress from control bar test |
| JCI | Derived using secant modulus at 0.7 $f_y$ and $f_y$ at 0.2% yield strain from the connection system tensile test |
| ISO | Use nominal yield strain, 0.2% |

Similar to that of the static conditions, it was concluded that two categories need to be considered, and they are:

- Strength; and
- Serviceability Limit State.

It was understood that considering the above two categories could provide sufficient knowledge for safety in seismic conditions.

### 2.3.1 *Strength and Serviceability Limit State*

The same logic as for the static conditions applied for both the strength and the serviceability limit state requirement. In addition to this, it was understood that limiting crack width due to slip could prevent local bending in a reinforced concrete member, consequently avoiding rigid body rotation of the member.

[1] Refer Appendix A. for abbreviations

## 3 RECOMMENDATIONS FOR UPCOMING REVIEW OF NEW ZEALAND STANDARD

As mentioned earlier, for upcoming review of the New Zealand reinforced concrete standard, NZS 3101: 1995, the following criteria are recommended for validating the performance of mechanical connection system in both static and seismic conditions.

### 3.1 Static Conditions

A high strength mechanical connection to be used in members shall satisfy the following two conditions:

- Strength - A mechanical connection shall develop a minimum tensile load of $\left(\frac{R_{mk.U}}{f_y}\right) f_y A_s$;
- Serviceability Limit State – Slippage within mechanical connection system shall be less than the allowable crack width listed in Table 3.4 of NZS 3101: 1995, when tested in accordance with the test regime presented here in Appendix B; and
- Fatigue Loading Situation – A mechanical connection that is to be subjected to fatigue loading shall be tested in a manner replicating the expected stress magnitude and number of cycles.

The overstrength factor, $\left(\frac{R_{mk.U}}{f_y}\right)$, to the allowable tensile force requirement for mechanical connectors in reinforced concrete members is imposed for safety. The reason for applying this overstrength factor is to prevent brittle failure of the mechanical connector in the connection system. The overstrength factor is decided to be 1.5 based on theoretical population distribution of threaded reinforcing bars widely used in New Zealand. It is noted that determination of this factor is the subject of an on going study, and this overstrength factor may change in future.

As the effective area that transfers stress through a mechanical connection system changes over its length, thus affecting stiffness of the connection system, it is appropriate to use units of force rather than stress when testing the connection system.

It is understood that slip occurrence within a mechanical connector under load will lead to surface cracking, hence it is a serviceability matter. It also is understood that the stiffness of the connection system, when encased in concrete, tends to be higher than that of the connection system tested in air. Therefore, it is decided that using the allowable surface crack width limits listed in Table 3.4 of NZS 3101: 1995 for the slip limit is appropriate.

Serviceability loading magnitude for verifying the appropriateness of mechanical connection systems is chosen as 60% of yield stress of the spliced reinforcing bars. This value was selected recognising that the majority of New Zealand concrete structures have been designed to sustain this load. Creep effects were also considered, so applying three cycles of serviceability load is proposed.

The use of mechanical connection systems in fatigue loading situation shall be the subject of a special study. It is proposed that such connection systems should be subjected to design level loading for stress range and number of cycles.

### 3.2 Seismic Conditions

Mechanical connections to be used in members that are subjected to seismic forces shall comply with the following conditions:

- Such mechanical connections shall be subjected to an elastic cyclic test and a plastic cyclic test as defined in Table 3 in accordance with the test regime presented in Appendix B; and
- Such mechanical connections shall comply with specified limit criteria in Table 4.

**Table 3. Seismic Load Sequence**

| Test Description | Loading Application | | | |
|---|---|---|---|---|
| | **Stage** | **Load** | | **No. of Cycles** |
| | | **Tension** | **Compression** | |
| Elastic Cyclic Test | 1 | 0 | | |
| | 2 | 0.95 $F_{ya}$ | 0.5 $F_{ya}$ | 20 |
| | 3 | tensile load till the sample fails | | |
| | **Stage** | **Load** | | **No. of Cycles** |
| | | **Tension** | **Compression** | |
| Plastic Cyclic Test | 1 | 0 | | |
| | 2 | 2 $\varepsilon_{ya}$ | 0.5 $F_{ya}$ | 4 |
| | 3 | 5 $\varepsilon_{ya}$ | 0.5 $F_{ya}$ | 4 |
| | 4 | tensile load till the sample fails | | |

**Table 4. Acceptance Criteria**

| Test Description | Acceptance Criteria | |
|---|---|---|
| Elastic Cyclic Test | Strength | $\left(\frac{R_{mk.U}}{f_y}\right) f_y A_s$ |
| | Slippage | Table 3.4 of NZS 3101: 1995 |
| Plastic Cyclic Test | Strength | $\left(\frac{R_{mk.U}}{f_y}\right) f_y A_s$ |
| | Slippage | 0.3 mm after first 4 cycles, 0.6 mm after second 4 cycles |

All mechanical connection systems need to be subjected to the both cyclic tests in accordance with the test regime presented in Appendix B in order to be verified for use in New Zealand.

The same overstrength factor as for static conditions is recommended to ensure avoiding premature failure of mechanical connection systems.

The same loading sequence used by JCI, ICBO, and ISO has been adopted.

The slip limit for the plastic cyclic test mentioned in the above table is extracted from ISO/CD 15835. It is believed that their slip requirement is the strictest, preventing rigid body rotation of reinforced concrete members due to connection slippage.

## 4 INDICATIVE TEST RESULTS USING THE RECOMMENDED TEST REGIME

Four types of testing in air were conducted using products of Reid Engineering Systems Ltd in order to demonstrate indicative use of the testing protocol recommended. All tests were carried out using a universal machine in the Civil Material Laboratory at the University of Auckland. It is noted that the results presented in this paper are preliminary only, and further work is under progress.

### 4.1 Control Bar Test

Three reinforcing bars (16 mm, 500E) from Pacific Steel Ltd. were subjected to a uni-axial monotonic tensile test to obtain the sample batch’s mechanical properties. The results are listed in Table 5.

**Table 5. Mechanical Properties of Control Bars**

| Sample | Yielding Load (kN) | Young's Modulus (GPa) |
|---|---|---|
| #1 | 112 | 204.6 |
| #2 | 113 | 217.9 |
| #3 | 111 | 186.4 |
| Average | 112 | 203.0 |

Based on the above average yield load and Young's modulus, and using nominal cross sectional area of the reinforcing bar, $A_s$, the average yield strain, $\varepsilon_{ya}$, was computed as:

$$\frac{f_{ya}}{E_a} = \varepsilon_{ya} = 0.00274$$

### 4.2 Strength Test

Three coupler specimens were strength tested in the manner corresponding to static load conditions. Each specimen consisted of a RB16 coupler connecting two 400 mm threaded Reidbars. All specimens experienced ultimate tensile failure of the spliced reinforcing bar before ultimate failure of the couplers (refer Fig.1).

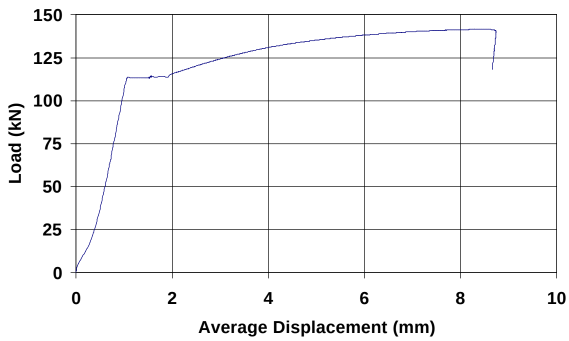


Figure 1. Indicative result of a Mechanical Connection System subjected to Tensile Test

### 4.3 Slip Test

Three specimens consisted of a RB16 coupler and 400 mm threaded Reidbar were initially set up for the slip test requiring 3 cycles between 0 and 0.6 $F_{ya}$. It was found that these specimens just met the requirement (see Fig. 2.), so a new set of tests was conducted with modification to the specimens. Reidbar torquenuts were used to prestress the spliced reinforcing bars. A preliminary exercise to determine the relationship between prestressing load magnitude and angle of turning the torquenuts was conducted. It was found that about $90^o$ turn from the finger-tight position would apply about 55 kN for this bar size. However it was understood that further work on "turning VS prestressing load" was necessary to establish a sufficiently reliable relationship. As shown in Fig. 3, this modification removed most of the slip occurrence.

### 4.4 Elastic Cyclic Test

Elastic cyclic tests were conducted on a RB 16 coupler. To avoid buckling of the specimen under compression, the effective specimen length excluding the grips on both ends was shortened to about 300 mm and torquenuts were attached to the specimen to increase stiffness. As shown in the figure below (fig. 4), the system met the proposed slippage requirement listed in Table 4.

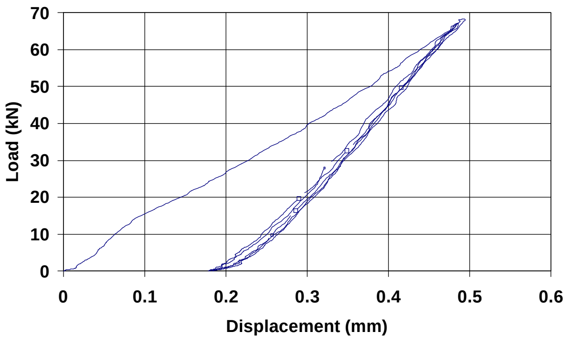


Figure 2. Indicative outcome of slip test: Sample without torquenuts

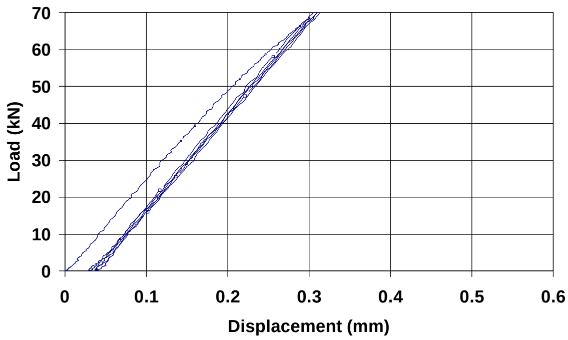


Figure 3. Indicative outcome of slip test: Sample with torquenuts

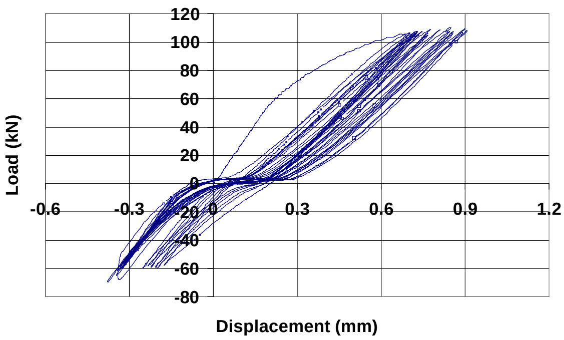


Figure 4. Indicative test result of elastic cyclic test

### 4.5 **Plastic Cyclic Test**

The same sample configuration as that of the elastic cyclic test was used to conduct plastic cyclic testing of a RB 16 coupler. Figure 5 represents performance of the system after the first four cycles. Analysis in accordance with the Appendix B was carried out to compute the slip occurrence of 0.19 mm. Similarly, the slip found after the second four cycles was 0.5 mm (see Fig.6).

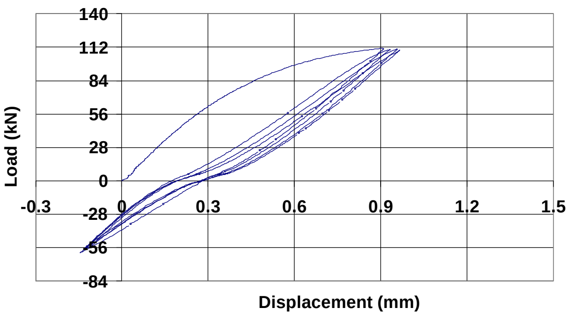


Figure 5. Indicative result of plastic cyclic load: Test after the first four plastic cycles

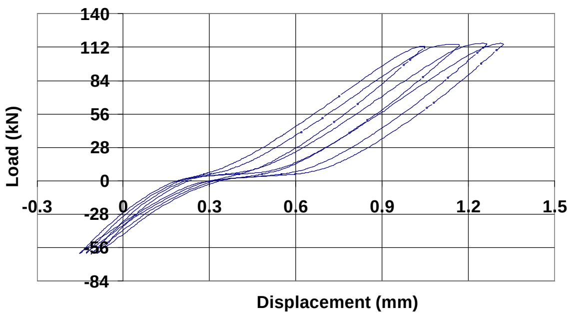


Figure 6. Indicative result of plastic cyclic load: Test after the second four plastic cycles

## 5 CONCLUSIONS

- The purpose of this research was to provide recommendations for use of mechanical connection systems in both static and seismic conditions.
- The research was motivated by the facts that the current criteria in New Zealand reinforced concrete standard, NZS 3101: 1995 were based on 1977 research, while there had been advancement in this field worldwide in recent years.

- New criteria on use of mechanical connection systems in both static and seismic conditions were proposed for the upcoming review of NZS 3101: 1995.
- Three criteria were proposed for use of mechanical connection systems in static conditions, being strength, serviceability limit state, and fatigue loading situation.
- Two criteria were proposed for use of mechanical connection systems in seismic conditions, being strength and serviceability limit state.
- Preliminary tests indicated that mechanical connection systems commonly used in New Zealand met the proposed criteria.

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## APPENDIX A: LIST OF SYMBOLS AND GLOSSARY OF TERMS

*List of Symbols*

$A_s$: nominal cross sectional area of reinforcing bar

$E_a$: actual average Young's Modulus

$F_{ya}$: actual average load at yielding of reinforcing bar

$R_{mk.U}$: theoretical upper characteristic value of ultimate tensile stress of reinforcing bar with 90 % confidence

$f_y$: specified yield stress of reinforcing bar

$f_{ya}$: actual average yield stress of reinforcing bar

$\varepsilon_y$: specified yield strain of reinforcing bar

$\varepsilon_{ya}$: actual average yield strain of reinforcing bar

*Glossary of Terms*

NZS: New Zealand Standard

JCI: Japan Concrete Institute

ISO: International Organisation for Standardisation

ICBO: International Conference of Building Officials

## APPENDIX B: TESTING PROTOCOL

Descriptions on four types of testing to verify performance of reinforcing mechanical connection systems are presented in this testing protocol.

### Prerequisites

Load-Displacement graphs shall be produced for every test.

- *Specimen*

Specimen length shall be sufficiently long to provide effective grips on both ends and gauge length. The mechanical connector shall be placed at the centre of the specimen.

For each test, a minimum of three specimens shall be tested accordingly.

- *Gauges*

A minimum of two gauges shall be placed at a plane for testing for static conditions. A minimum of three gauges shall be placed at $120^o$ apart. Average value of these gauges is to be reported.

Gauges shall measure elongation over mechanical connector. It is recommended to place gauges on spliced reinforcing bars and place them as close as possible to the mechanical connector.

- *Basic Acceptance Criteria*

All three specimens shall meet criteria mentioned in Section 3.

## Control Bar Test

A minimum of three specimens from the same batch shall be subjected to tensile testing in order to obtain actual average yield load, actual average yield strain, actual ultimate tensile load, and actual average Young's modulus.

## Static Conditions

- *Strength Test*

All samples shall be subjected to tensile test. Tensile failure of spliced reinforcing bar is expected. In order to verify actual tensile load capacity of mechanical connectors, high strength bars may be used. However, it is acceptable to have specimens experiencing reinforcement failure, as long as actual average ultimate tensile load of the reinforcing bar is reached.

- *Slip Test*

All samples shall be subjected to slip test. Three cycles of 0 to 60 % of specified yield load (using nominal cross sectional area) of spliced reinforcing bar shall be applied. The slip is defined as residual deformation, which is the elongation at 0.02 $F_y$ after the three loading cycles.

## Seismic Conditions

- *Elastic cyclic Test*

All samples shall be subjected to elastic cyclic test. Twenty cycles of 0 to 95 % of actual average yield load of spliced reinforcing bar shall be applied. The slip shall be the residual elongation after twenty cycles.

- *Plastic Cyclic Test*

All samples shall be subjected to plastic cyclic test. The loading sequence specified in the table below shall be applied.

**Table A-1. Loading sequence for plastic cyclic test**

| Stage | Loading Application | | |
|---|---|---|---|
| | Tension | Compression | Cycles |
| 1 | $2\varepsilon_{ya}$ | 0.5 $F_{ya}$ | 4 |
| 2 | $5\varepsilon_{ya}$ | 0.5 $F_{ya}$ | 4 |

The yield strain is to be assessed based on mechanical properties gathered from the control bar test. Use actual average yield stress using nominal cross sectional area of reinforcing bar and actual average Young's modulus; calculate average yield strain.

Once the yield strain is found, find the average magnitude of loads, $2\varepsilon_{ya}$ and $5\varepsilon_{ya}$, from the three load-displacement graphs produced in control bar test.

To find slip, see Fig. B-1.

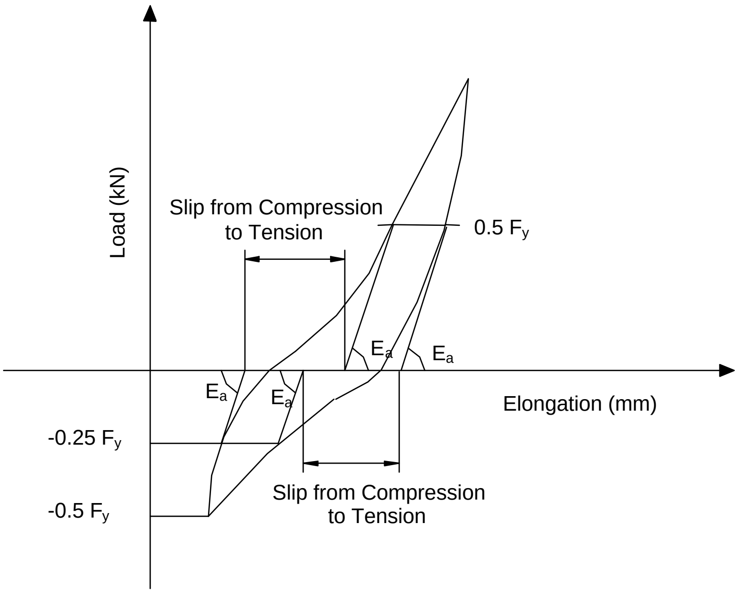


Figure B-1. Slip assessment for plastic cyclic test