Narratives of Sustainable Development: Industry in the Global World Meeting Social Ecological Responsibility

introduced by

Prof Bernard Adeney-Risakotta

Courtesy of painting by Vincent van Gogh, Lady Alies

MUP Muhammadiyah University Press
International Conference Committee 2010-2011
# TABLE OF CONTENTS

| i.  | Title                                      | i |
| ii. | Preface                                    | iii |
| iii. | Acknowledgments                           | vii |
| iv.  | Table of Contents                          | ix |
| v.   | Introduction                               | xii |
|      | BERNARD ADENEY-RISAKOTTA: Is There a Meaning in Natural Disasters? Construction of Culture, Religion and Science | |

## Part I Innovative Science and Technology for Sustainable Development

1. MUSLICH HARTADI SUTANTO: Effect of Bond on Pavement Performance toward Efficient Use of Natural Resources in Road Construction
2. HUSNI THAMRIN: Embracing Open Source Software to Empower Potentials of Community
3. QUNIK WIQOYAH & BUDI LISTYAWAN: Study of Shear Strength Parameter of Lime Trass Stabilization on Clay: Ways to Improve Soil Strength
4. SRI SUNARJONO: Introduction to a Sustainable Pavement Construction using Foamed Cold
5. H.R.A. YAMIN & SIEGFRIED: Laboratory Performance of CTAM Under Indonesian Tropical Climate
6. MAMOK SUPRAPTO: Sustainable Water Infrastructure Using Turbulent Flow as Sediment Control
7. ARBI HAZA NASUTION & SALHAZAN NASUTION: Online Prenatal Appointment Management System
8. INDAH PRATIWI, ETIKA MUSLIMAH, & R. KUSBIMANTORO SETYOJATI: Redesign of Equipment and Work Methods in Tofu Industries
9. TRI TJAHJONO, MARWAN EFFENDY, & PARDAM: Influences of Vertical Cylinder Cyclone Separator Size on the Gas-Liquid Separation

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<table>
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</tr>
<tr>
<td>9</td>
<td></td>
<td>126</td>
</tr>
</tbody>
</table>
Table of Contents

10. RINI HIDAYATI, NUR RAHMAWATI SYAMSUYAH, & PRIYONO NUGROHO: Model of Mosque Site Based on Noise Reduction Analysis 144
11. ROHANI JAHJA WIDODO: Control System is an Applied Mathematic 159
13. N. HIDAYATI: Is Updating the Passenger Car Equivalent Value still needed in Road Capacity Analysis? 184
14. MUHAMMAD MUJIBUROHMAN: The Use of Artificial Neural Networks for Determining the Relative Importance of Affecting Variables on Outputs of Developed Technologies 197
15. ANTO BUDI LISTYAWAN & RENANINGSIH: Statistical Characterization of Cone Penetration Test Variability for Ibis Hotel Soil 203
16. KRISNA DWI HANDAYANI, I GUSTI NGURAH ANTARYAMA, & HAPPY RATNA SANTOSA: Study of Wind Behavior around Buildings on Fishing Settlement: Contributing Information of Ventilation 216
17. YENNY NURCHASANAH: Force Distribution and Ductility Behavior of Reinforced Concrete Coupling Beams with Diagonal Reinforcement 233
18. SAMSUDI RAHARDJO & SOLECHAN: Manufacturing Piston from Waste Piston Material by Inserting Cast Iron and St 60 of Piston Compressive Ring Groove 251
19. HARYOTO: Secondary Metabolites from the Tree Bark of Shorea Accuminatissima 265

Part II Social Ecological-Environmental Responsibility

20. WIWIT RAHAYU & ERLYNA WIDA RIPTANTI: The Development Strategy of Poor Household’s Food Security in the Flood-Prone Areas in Surakarta 277
21. IKA SETYANINGSIH: Traffic Noise Level Comparison between Direct Measurement and Empirical Equation on Several Education Zones in Surakarta: Noise Mitigation for Students 283
22. M. SYARIF HIDAYAT: Urban Green Space to Achieve Urban Green Space to Achieve Sustainable Development: Learning from Urban Green Spaces in Jakarta 307
23. JAJI ABDURROSYID & ANTO BUDI LISTYAWAN: Environmental-Friendly Countermeasure for River Bank Scouring: Bio-Engineering as an Alternative Solution 316

**Part III Impacts of Industrialization on Poverty and Consumers’ Rights**

25. KUSSUDYARSANA: Investigating Role of Family in Success of Business Start-Up for Sustainable Economy 339
26. RINI KUSWATI: Nested Model of Analyzing Influence of Time Orientation on Behavior of Avoiding Television Advertising 355
27. FAJAR S. HANDAYANI: Strategy Management of National Private Contractor and Consultant in Facing Free Investment Era 374
28. AHMAD MARDALIS, MUMTAZAH OTHMAN, NURIZAN YAHAYA, SYARIFAH AZIZAH HARON, & ROSLI SALLEH: The Antecedents of Customer Loyalty in Muhammadiyah Education Institution 394

**Part IV Industry in the Perspective of Cultural, Psychological and Educational Innovation**

29. WINARSIH NUR AMBARWATI & ABI MUHLISIN: Effectiveness of Couple Cares Model to Increase Husband Participation in Family Planning Program for the Poor Family in Kartasura, Sukoharjo, Central Java 409
30. MOORDININGSIH: Psychological Climate and Human Performance: Effectiveness and Efficiency 422
31. MUCH DJUNAIDI, TOTOK BUDI SANTOSO, & WAHYUNI: Model of Technological Innovation Using BTC-SMK to Support SME’s Competitiveness Development 441
32. LUSI NURYANTI, WTIWIEN DINAR PRASTITTI, & FITRI ASTUTI: Increasing Verbal Creativity through Traditional Games for Primary School Children 453
33. ENDAH SUDARMILAH, ABDUL BASITH, & RIWANTO: Culture Map Application of Indonesia: Effort to Achieve Cultural Sustainability 466
34. ENDANG TRININGSIH: Cafes of Bandung: ‘Autochthonous Coffeehouse Cultures in Contemporary City 475
Abstract—Beams with coupling force have been designed as conventional flexure members with stirrups and with some shear resistance allocated to the concrete are oftentimes will inevitably fail specially at diagonal areas, hence for beams with coupling force is recommended that the beams are reinforced with diagonal systems (bi-diagonal reinforcement). Six object test coupling beams 400 x 300 x 150 mm have been tested to aim the target, which is to know the behavior characteristic of deformation and mode of failure, to know the placement influence of diagonal reinforcement at coupling beams. Result of research indicate that behavior characteristic of deformation and mode of failure at coupling beams that happened is the existence of compression area at diagonal direction coming in contact with tip of force, tension area at opposite diagonal direction which will have crack till split at diagonal area compress, and the beam will attain its maximum load carrying capacity when small portion of the concrete in the compression corners crush. The proposed method of analysis of reinforced concrete coupling beams based on the equilibrium of forces of triangular half of the beam at failure gives a satisfactory prediction the distribution of force in the main bars. The behavior of coupling beams in shear (diagonal splitting) mode of failure is represented in mathematical model.

Index Terms—Coupling beams; CRT Bar; ductility; diagonal reinforcement; force distribution

I. INTRODUCTION

The phenomena of couple shear walls has evolved recently through the increase in the number of high-rise masonry building being erected for both residential and commercial purposes, for example, apartment and hotels.

Multistory shear walls with openings present a number of problems. If the openings are very small, their effect on the overall stress minor. However, large openings have much more pronounced effect. Opening (windows, doors, and the like) normally occur in regularly spaced vertical rows throughout the height of the wall. So, their must to provide a structure that could be function to transfer the force between the vertical walls. For that purpose, hence provided a beams to connecting the walls.

The structural behavior of reinforced concrete couple shear walls is greatly influenced by the behavior of their coupling beams. The behavior of the coupling beams themselves depends on the geometry of the beams and the strength characteristics of the concrete and reinforcement.

Many beams with coupling force have been designed as conventional flexure members with stirrups and with some shear resistance allocated to the concrete are oftentimes will inevitably fail specially at diagonal areas, hence for beams with coupling force is recommended that the beams are reinforced with diagonal systems (bi-diagonal reinforcement)

One of the focus in this research is comparing two different bar type at its diagonal systems that is between deform type and of CRT Bar type (see Fig. 5). Cold Rolled & Twisted bar (CRT Bar) is made steel bar with process of cold rolled at steel wire rod and then twisted.

This research gives some target, there are:

1. To know the behavior characteristic of deformation and mode of failure between conventional coupling beams with coupling beams with diagonal reinforcement placing.
2. To know the placement influence of diagonal reinforcement at coupling beams (Deform and also of CRT Bar).
3. To know the influence of difference of bar type at diagonal reinforcement, that is between deform type Ø10,0 mm with CRT Bar type Ø8,0 mm.
4. To describe the concept of the structural behavior of reinforce concrete coupling beams. A mathematical model of beams at failure is put forward and a method for the ultimate load analysis of reinforced concrete coupling beams is presented. It is considered that the proposed method of analysis is consistent with the actual behavior of the beams.

II. ANALYSIS

Reinforcement Design:
Gravity load effects on these beams are neglected.
It is recommended that in coupling beams of structural walls, the entire seismic design shear and moment should be resisted by diagonal reinforcement in both directions.

Maximal allow shear stress:

\[ V_{\text{max}} = 0,1 \cdot l_n \cdot \sqrt{f_c^*} / h \] (MPa)

\[ V_{\text{max}} = 1,2 \cdot (l_n / h) \cdot \sqrt{f_c^*} \] (psi)

Minimum allow shear stress:

\[ V_{\text{min}} = Q_u / (\phi \cdot b_w \cdot d) \] ; \( \phi = 0,85 \)
If $v_{\text{min}} > v_{\text{max}}$, diagonal reinforcement should be used in all coupling beams to resist the entire earthquake-induce shear force.

![Diagram of coupling beams](image1)

**Fig 1.** Force direction and notation of coupling beams

From Figure 1, it is seen that the diagonal force are:

$$C_u = T_u = \frac{Q}{2 \sin \alpha}$$

The area of diagonal steel required is:

$$A_{sd} = \frac{T_u}{f_y} \phi = 0.9 \frac{Q}{2 f_y \sin \alpha} \text{ (MPa)}$$

Transverse reinforcement area required is:

$$A_{te} = \frac{\sum A_s f_y}{16 f_y} \cdot \frac{s}{100} \text{ (mm)}$$

where, $s \leq 100 \text{ mm}$

$s \leq 6 \cdot d_b \text{(D-diagonal)}$

$s \leq 24 \cdot D \text{-sengkang}$

Development length required is:

$$l_{db} = \frac{1.38 A_s f_y}{c \sqrt{f_y}} \text{ (mm)}$$

where, $2c_s$ is center-to-center distance between bars in the vertical plane.

The development length of this group of four bars is, however, to be increased by 50%.

$$l_d = 1.5 \times l_{db} \text{ (mm)}$$

When transverse ties are also used within the wall, the development length may be reduced with:

$$k_{tr} = \frac{A_{tr} f_{tr}}{10 s}$$

with reduction factor:

$$\frac{c}{c + k_{tr}}$$

and thus,

$$l_d = \text{reduction factor} \times 1.5 \times l_{db} \text{ (mm)}$$

### III. DEFORMATION

The real deformation of the coupling beams is a combination of the flexural and shear deformations. But in any particular case, either flexure or shear will govern. When **flexure** governs, the overall deformation of the beam is still accurately represented by flexure type deformation (Fig. 2) and as in (1) is reasonably accurate for estimating the ultimate strength of the beam.

$$P_u = \frac{2h}{\alpha} A_y f_y$$  \hspace{1cm} (1)

**Shear Deformation**

A pure shear deformation and the actions produced in the beam are shown in Fig. 3(a) and Fig. 3(b). The pure shear deformation requires both top and bottom surfaces of the beam all along the length to be tension. There is compression along the diagonal AC and tension along BD. An element of the beam near the mid span is subjected to a biaxial compression tension state of stress. The concrete crack when the tensile stress in the concrete along the diagonal BD reached the limiting tensile strength of concrete.

The mode of failure in shear is characterized by the extension of the diagonal crack up to the position of the main reinforcement diagonally opposite and by the crushing in the compression corners (Fig. 3b)

![Diagram of shear deformation](image2)

**Fig. 3a.** Initial stage: element under biaxial stage

**Fig. 3b.** Final stage: Diagonal splitting and crushing of concrete

When the behavior is governed by shear, the overall deformation of the beam is much more complex. The flexural deformation causing the beam to bend in double curvature, with tension along one-half of the beam changing into compression along the other half on both top and bottom surfaces, conflict with the shear deformation which causes the beam to go into tension on both surfaces along entire length.
IV. DUCTILITY DEFORMATION

Ductility defines the ability of a structure and selected structural component to deform beyond elastic limits without excessive strength or stiffness degradation [4].

The most convenient quantity to evaluate the ductility imposed on structure by an earthquake, or the structure’s capacity to develop ductility, is displacement. The displacement ductility is:

$$ \mu_D = \frac{\Delta}{\Delta_y} $$

Where, $\Delta = \Delta_y + \Delta_p$. The yield ($\Delta_y$) and fully plastic ($\Delta_p$) component of the total lateral tip deflection $\Delta$.

**Coupling Beams Analysis**

The analysis of coupling beams subjected to flexural and shear stress actions, and in which the structural behavior is governed by shear, may be carried out by considering the force system in a triangular half of the beam as shown in Fig. 4.

![Fig. 4. idealized diagram : equilibrium of triangular half of the beam](image)

The following equation may be written:

Vertical equilibrium:

$$ P_u = 2.V + f_{tc}.b.a + P_v $$

Horizontal equilibrium:

$$ P_{st} = f_{tc}.b.h' + P_h + C $$

moment about 0 ($M=0$):

$$ P_{sh'} = V.a + f_{tc}. \frac{b(h^2+a^2)}{2} + P_h. \frac{h'}{2} + P_v. \frac{a}{2} $$

From eqns. (2) to (4), the ultimate load for the beam may be expressed as

$$ P_u = (f_{tc}.b.h' + 2.C + P_h). \frac{h'}{a} $$

In proposing equation (5) the most important criteria for the failure of coupling beams is assumed to be the crushing of the concrete of depth (h-h') / 2 in highly stressed compression corners. The compressive force, $C = 0.67 f_{tu}.b.(h-h')$ / 2

The quantity $f_{tc}.b.h$ and contribution of $P_h$ depends on whether the web strength is controlled by concrete or by reinforcement.

### Control of Web Strength and Contribution of Web Reinforcement

The web reinforcement consists of horizontal web bars placed in the central part of the beam between the top and the bottom main bars and vertical stirrups. The control of web strength and contribution of the web bars depends on the relative capacities of the concrete splitting force and the web reinforcement. The following criteria tests may be applied:

When the web strength I controlled by reinforcement, $P_h = \lambda_1 A_b f_{sy}$, $P_v = \lambda_2 A_v f_{sy}$ and $f_{tc}$ will not contribute. Here, $\lambda_1, \lambda_2 = 1$. When the web strength is controlled by concrete, $P_h = A_b f_{cu}$, $P_v = A_v f_{cu}$ and $f_{tc}$ will contribute.

Here, $f_c = \text{modulus ratio} \times f_{cu}$ and $\lambda_1$ and $\lambda_2$ are factors which depend on the geometric parameters.

<table>
<thead>
<tr>
<th>Test</th>
<th>$f_{tc}.b.h' + A_b f_c$</th>
<th>$f_{tc}.b.a + A_v f_c$</th>
<th>Web strength is controlled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>$&lt; A_b f_{sy}$</td>
<td>$&lt; A_v f_{sy}$</td>
<td>reinforcement</td>
</tr>
<tr>
<td>(b)</td>
<td>$&gt; A_b f_{sy}$</td>
<td>$&gt; A_v f_{sy}$</td>
<td>concrete</td>
</tr>
</tbody>
</table>

The criteria tests indicate clearly that, for the web reinforcement to be effective, sufficient amount must be provided in both directions, i.e. horizontal and vertical. If sufficient reinforcement is present in one direction only, e.g. closely spaced vertical stirrups but no additional horizontal bars, the effectiveness of the reinforcement will be small.

The introduction of factors, $\lambda_1$ and $\lambda_2$, suggests that, for a better utilization of the web reinforcement must be provided in the same proportion as the components of the concrete splitting force. When the web strength is governed by the reinforcement and also when the proportion of the reinforcement in the horizontal and the vertical directions is in the ratio.

$$ \frac{(f_{tc}.b.h' + A_b f_c)}{(f_{tc}.b.a + A_v f_c)} = \lambda_1 = \lambda_2 = 1 $$

That represents an efficient use of the web bars.

### Contribution of Main Reinforcement

The contribution of the main bars may be examined from equation (3). Since the compressive force, $C$, is assumed to be equal to $0.67 f_{tu}.b.(h-h')$ / 2 at failure, $P_{st}$ can calculated. Now, if $P_{st}$ is less than the capacity of the main bars, $A_{st} f_y$, it is assumed that the main bars will not yield at the failure of the beam. If $P_{st}$ is greater than $A_{st} f_y$, the main bars will yield at failure.
**Force Distribution in Main Bars**

It is assumed that the force in the main bars varies linearly from $T_o$ at the tip of the triangular half (Fig. 4) to $T_s$ at the support. For the evaluation of $T_o$, equation (2) is expressed as

$$V = \frac{1}{2} \cdot (p_{u2} - f_{ct} \cdot b \cdot a - P_v)$$  \hspace{1cm} (6)

in which $p_{u2}$ is calculated from equation (5) and the contribution of the other quantities is obtained as appropriate, i.e. based on whether the control of web strength is by concrete or by reinforcement. Then, referring to Fig. 4, the force in the main bar near the tip of the triangle may be obtained from

$$T_o = \frac{V}{h'}$$  \hspace{1cm} (7)

the force in the bar at the support, $T_s$, is evaluated from equation (3), as discussed earlier.

**V. RESEARCH METHOD**

This research pertained experimental laboratory research where the parameters used to be based to the theoretical analysis.

The analysis are:

- Theoretical analysis where some parameters that relevant to predict the deformation behavior of coupling beams. This analysis will produce the theoretical values.
- Experimental analysis where the data from analysis theoretical to be treated to the specimens (coupling beams). This analysis will produce the experimental values.

**Specimen (model)**

<table>
<thead>
<tr>
<th>Code</th>
<th>Dimension BxHxT (mm)</th>
<th>Diagonal Reinforcement</th>
<th>Diameter $\Theta$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK-1</td>
<td>400x300x150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BK-2</td>
<td>400x300x150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD-1</td>
<td>400x300x150</td>
<td>Deform</td>
<td>10,0</td>
</tr>
<tr>
<td>BD-2</td>
<td>400x300x150</td>
<td>Deform</td>
<td>10,0</td>
</tr>
<tr>
<td>BT-1</td>
<td>400x300x150</td>
<td>CRT Bar</td>
<td>8,00</td>
</tr>
<tr>
<td>BT-2</td>
<td>400x300x150</td>
<td>CRT Bar</td>
<td>8,00</td>
</tr>
</tbody>
</table>

**Failure Process**

Deformation that happen on coupling beams in this experiment is a combination of the flexural and shear deformation Behavior characteristic of deformation and mode of failure at coupling beams that happened is the existence of compression area at diagonal direction coming in contact with tip of force, tension area at opposite diagonal direction which will have crack till split at diagonal area compress, and the beam will attain its maximum load carrying capacity when small portion of the concrete in the compression corners crush.

This behavior requires fresh explanation and may be described as follows (see Fig. 6):

(i). At early stage of loading, the beam starts to deform in common flexural type behavior (Fig. 6a). At this stage, the beam has double curvature with a line of contraflexure at the center of the span. A line of contraflexure is defined as the line passing through the points of contraflexure of the horizontal layers of the beam. But soon after, when the shear force is large enough to initiate a diagonal crack, the double curvature (flexure) behavior changes.

(ii). As the crack opens up because of increasing diagonal tension compression effect, the outer concave part of the curvature on both top and bottom surfaces of the beam pushes outward gradually. This is equivalent to a shift in the position of the points of contraflexure in reinforcement from their original position at the center towards the supports in the opposite direction. It can be visualized from Fig. 6b that the line of contraflexure rotates anticlockwise as the diagonal crack in the concrete spreads outwards from the center.

(iii). The shift in the position of the point of contraflexure in the reinforcement will stop near the fixed end support where the conflicting deformation required for the bending and shear action cause the reinforcement to kink (Fig. 6c). At this stage, the concrete will have cracked most of the way diagonally showing a marked separation near the middle. The reinforcement, both top and bottom, will be in tension along most of its length except near the kink where the local affect will influence the behavior.

(iv). The beam will attain its maximum load carrying capacity when small portion of the concrete in the compression corner crush, thus marking the failure of the beam (Fig. 7).
Fig. 6a. Early stage: flexural behavior

Fig. 6b. Diagonal splitting and rotation of the line of contraflexure

Fig. 6c. Final stage at failure: Final deformed shape

Crack Pattern and Split
The diagonal split wide values of coupling beams with diagonal reinforcement placing (Deform and also of CRT Bar) is 1.35 cm, and the diagonal split wide value of conventional coupling beams is 2.75 cm. From this data proved that coupling beams with diagonal reinforcement can lessen widely of split up to 50.91% compared to the wide of split at conventional coupling beams.

This result can be enabled to happen because with the existence of diagonal reinforcement addition in one group (four bars) hence will be formed a concrete core that can resist the tension stress at diagonal stress areas. The diagonal stress areas will be contrary direction with diagonal compress areas. Wide of diagonal split among usage both types of the steel bar do not show differ far.

<table>
<thead>
<tr>
<th>Spec. Code</th>
<th>Split Wide (cm)</th>
<th>P(_{\text{first crack occurs}}) (kN)</th>
<th>P(_{\text{split}}) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK</td>
<td>2.75</td>
<td>112.20</td>
<td>114.84</td>
</tr>
<tr>
<td>BD</td>
<td>1.35</td>
<td>128.70</td>
<td>135.96</td>
</tr>
<tr>
<td>BT</td>
<td>1.35</td>
<td>115.50</td>
<td>118.80</td>
</tr>
</tbody>
</table>

TABLE III
CAPACITY AND SPLIT

Fig. 7. Kink area
TABLE IV
COMPARISON BETWEEN THEORETICAL ANALYSIS WITH EXPERIMENTAL ANALYSIS

<table>
<thead>
<tr>
<th></th>
<th>BD-1</th>
<th>BD-2</th>
<th>BT-1</th>
<th>BT-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu, theoretical (kN)</td>
<td>178,648</td>
<td>94,646</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu, experimental (kN)</td>
<td>125,40</td>
<td>135,96</td>
<td>121,44</td>
<td>116,16</td>
</tr>
<tr>
<td>mean</td>
<td>130,68</td>
<td>118,80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE V
COMPARISON ANALYSIS OF CONVENTIONAL COUPLING BEAMS BETWEEN EXPERIMENTAL AND THEORETICAL RESULT

<table>
<thead>
<tr>
<th>Mode of Failure</th>
<th>Pu, experimental (kN)</th>
<th>f_c' (N/mm²)</th>
<th>f_t (N/mm²)</th>
<th>Pu, flexural failure (kN)</th>
<th>Pu, shear failure (kN)</th>
<th>Predicted mode of failure</th>
<th>Ultimate load Pu, analysis (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear, major diagonal crack, concrete and steel stresses seriously disturbed at the compression corners.</td>
<td>114,84</td>
<td>21,073</td>
<td>26,341</td>
<td>217,841</td>
<td>112,1181</td>
<td>Shear, diagonal splitting and crushing of concrete at the compression corners.</td>
<td>112,1181</td>
</tr>
<tr>
<td>Shear, diagonal splitting with the crushing of the concrete at highly stressed compression corners.</td>
<td>0,9763</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The experimental observations of the modes of failures agree well with this prediction. The ultimate loads for the beams were predicted using equation (5). The ratios in the last row of Table V indicate that the analysis method can be used to predict the value and behavior of ductility at coupling beams. Pu analysis / Pu test, suggest that the predicted values agree well with the test result.

Displacement Ductility

Deflection value measured at the tip area of the beam that opposite with back part area that getting the force (load).

Read of deflection use the LVDT. The displacement ductility values is:

\[ \mu = \frac{\Delta_u}{\Delta_y} \]

Where, \( \mu \) = ductility

\( \Delta_u \) = deflection at ultimate load

\( \Delta_y \) = deflection at yield load

Deflection at yield (\( \Delta_y \)) took at first crack moment. Deflection at ultimate (\( \Delta_u \)) took if the beams reach maximum load that marked with split moment.

Structures response at six specimens shown that the ductility response included in Restricted ductility, because the structure have value of maximum displacement ductility (\( \mu_A \)) in interval 1,5 to 3,5.

TABLE VI
DISPLACEMENT DUCTILITY

<table>
<thead>
<tr>
<th>Spec. Code</th>
<th>Ductility (( \mu_A ))</th>
<th>( \mu ) (mean)</th>
<th>Improvement of ductility (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK-1</td>
<td>1,644</td>
<td>1,630</td>
<td>-</td>
</tr>
<tr>
<td>BK-2</td>
<td>1,616</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD-1</td>
<td>1,936</td>
<td>1,957</td>
<td>20,06</td>
</tr>
<tr>
<td>BD-2</td>
<td>1,978</td>
<td></td>
<td>9,269</td>
</tr>
<tr>
<td>BT-1</td>
<td>1,619</td>
<td>1,791</td>
<td>9,877</td>
</tr>
<tr>
<td>BT-2</td>
<td>1,962</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Force Distribution in Main Bars

The distribution of force in the main bars of the beams at failure is shown in Fig. 8. using he proposed concept, the force in the main bars, when the diagonal splitting mode of failure occurs, is tensile. The force varies linearly along the span with a smaller value at he tip of the triangular half of the beam to its full capacity at the support. Although it was not possible to compare the force directly with the experimental result, the observed behavior agrees with the proposed concept. The distribution of force in the bars based on the conventional concept of flexural deformation of reinforced concrete coupling beams differs drastically with the actual behavior (Fig. 8).

The proposed method of analysis, as in (1) to (5), was used to analyze the beams. In each case the first step was establish...
whether the web strength was controlled by concrete or by reinforcement. It is obvious that, in beams with only vertical stirrups, the control of web strength is by concrete, beams 1 is example. In beam 2 the proportion of web horizontal reinforcement is small, and the overall control is governed by concrete. In beam 3, 4, 5 & 6, there is adequate reinforcement in both the horizontal and vertical direction. Therefore the web strength is controlled by the reinforcement. The proportions are such that the strengths due to reinforcement are similar to those due to concrete. Therefore, in practice either can controlled the web strength.

Fig. 8. Theoretical distribution of forces in the main bars

VII. CONCLUSION

Behavior characteristic of deformation and mode of failure at coupling beams that happened is the existence of compression area at diagonal direction coming in contact with tip of force, tension area at opposite diagonal direction which will have crack till split at diagonal area compress, and the beam will attain its maximum load carrying capacity when small portion of the concrete in the compression corners crush. Mode of failure that happened is shear failure.

Result of comparison between conventional coupling beams (BK) with coupling beams with diagonal reinforcement placing (BD and also of BT) are : (a). Wide of diagonal split show BD and also of BT prove can lessen widely of split up to 50,91% compared to is wide of split at BK (b). Reinforcement placing specially at diagonal area compress can improve value of Ductility. At BT, the increase of ductility equal to 9,88% bigger to BK. At BD, the increase of ductility equal to 20,06 % bigger to BK.

Comparison of ductility value indicate that BD have value of ductility 9,27 % bigger compared to BT.

Ratio between $P_e$ (theoretical) with $P_u$ (experiment) is equal to 0,98, this number indicate that the analysis method can be used to predict the value and behavior of ductility at coupling beams.

The proposed method of analysis of reinforced concrete coupling beams based on the equilibrium of forces of a triangular half of the beam at failure gives a satisfactory prediction of force in the main bars.

VIII. REFERENCES

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IX. BIOGRAPHIES

Yenny Nurchasanah was born in Solo in the center of Java, Indonesia, on March 31, 1977. She graduated from Muhammadiyah University of Surakarta, central Java, Indonesia in 2000 and finished the master program at Brawijaya University, Malang, East Java, Indonesia in 2006. Her building design experience starts when she is in graduate program, she help her graduate lecturer to do a project, that is Concrete Design for four floors school in 1998. The last concrete designs that she has made are the five floors hospital building in 2009. She is good at operating some civil engineering soft wares. She has conducted some researches to improve her knowledge about concrete design and concrete materials. In addition to her academic activities as a lecturer, she is also responsible for some management and administrative tasks in her department such as to supervise in CAD/CAE laboratory.