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

Edited by
Dewi Candraningrum

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(Editor)

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Introduced by

Prof Bernard Adeney-Risakotta

Courtesy of painting by Vincent van Gogh, *Lady Arles*

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Force Distribution and Ductility Behavior of Reinforced Concrete Coupling Beams with Diagonal Reinforcement

Yenny Nurchasanah, *Lecturer of Civil Engineering*

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:

- To know the behavior characteristic of deformation and mode of failure between conventional coupling beams with coupling beams with diagonal reinforcement placing.
- To know the placement influence of diagonal reinforcement at coupling beams (Deform and also of CRT Bar).
- To know the influence of difference of bar type at diagonal reinforcement, that is between deform type Æ10,0 mm with CRT Bar type Æ8,0 mm.
- 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 :

$$V_{max} = 0,1 \,.\, l_n \,.\, \sqrt{f'_c} \;/\; h \quad (MPa)$$

$$V_{max} = 1,2 \,.\, (l_n / h) \,.\, \sqrt{f'_c} \quad (psi)$$

Minimum allow shear stress :

$$V_{min} = Q_u / (f \,.\, b_w \,.\, d) \quad ; \; f = 0,85$$

If $v_{min} > v_{max}$, diagonal reinforcement should be used in all coupling beams to resist the entire earthquake-induce shear force.

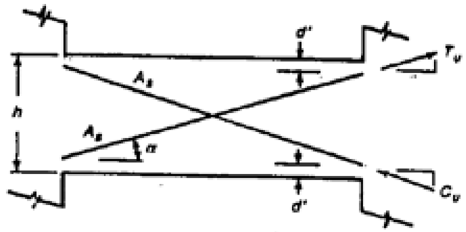


Fig 1. Force direction and notation of coupling beams

from figure **1**, it is seen that the diagonal force are :

$C_u = T_u = Q / (2.\sin \alpha)$

The area of diagonal steel required is :

$A_{sd} = T_u / (\phi . f_y)$; $\phi = 0,9$

$= Q / (2.\phi . f_y . \sin \alpha)$ (MPa)

Transverse reinforcement area required is :

$A_{te} = \frac{\sum A_b \cdot f_y}{16. f_{yt}} \cdot \frac{s}{100}$ (mm)

where, $s \le 100$ mm

$s \le 6 . d_b$ (D-diagonal)

$s \le 24$ x D-sengkang

Development length required is :

$l_{db} = \frac{1{,}38. A_b \cdot f_y}{c.\sqrt{f'_c}}$ (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%.

$l_d = 1{,}5 \times l_{db}$ (mm)

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

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

with reduction factor : $\frac{c}{c + k_{tr}}$

and thus,

l_d = reduction factor x $1{,}5 \times l_{db}$ (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.

$$P_u = \frac{2h}{a} . A_{st} . f_y \qquad (1)$$

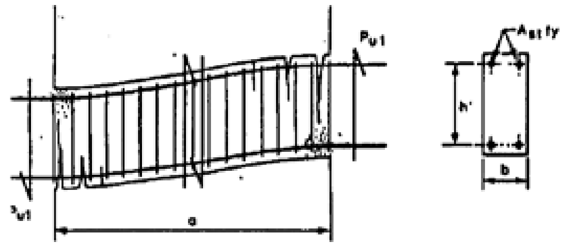


Fig 2. Flexural deformation of beam and force

Shear Deformation

A pure shear deformation and the actions produced in the beam are shown in **Fig. 3a** and **Fig. 3b**. 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**)

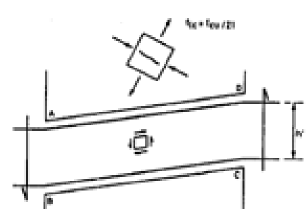
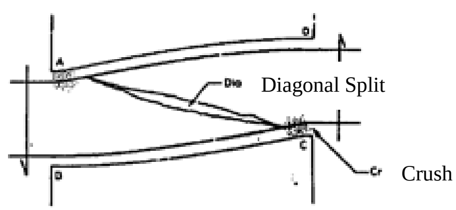


Fig. 3a. Initial stage : element under biaxial stage



Gbr. 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 :

$$m_D = \frac{D}{D_y}$$

Where, $D = D_y + D_p$. The yield (D_y) and fully plastic (D_p) component of the total lateral tip deflection D.

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**.

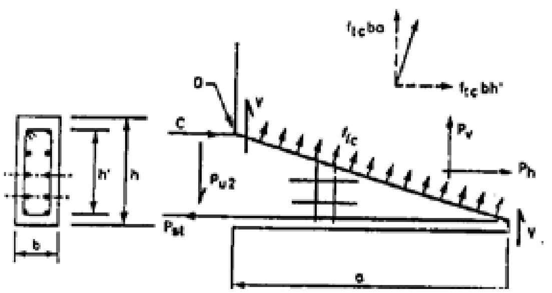


Fig. 4. idealized diagram : equilibrium of triangular half of the beam

The following equation may be written :
Vertical equilibrium :

$$P_u = 2.V + f_{tc}.b.a + P_v \qquad (2)$$

Horizontal equilibrium :

$$P_{st} = f_{tc}.b.h' + P_h + C \qquad (3)$$

momen about 0 (M=0) :

$$P_{st}h' = V.a + f_{tc}.\frac{b.(h'^2 + a^2)}{2} + P_h.\frac{h'}{2} + P_v.\frac{a}{2} \qquad (4)$$

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

$$P_u = (f_{tc}.b.h' + 2.C + P_h).\frac{h'}{a} \qquad (5)$$

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, $C = 0{,}67.f_{cu}.b.(h-h') / 2$
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, $P_h = l_1.A_h.f_{sy}$, $P_v = l_2.A_v.f_{sy}$ and f_{tc} will not contribute. Here, $l_1.l_2 = 1$. When the web strength is controlled by concrete, $P_h = A_h.f_s$, $P_v = A_v.f_s$ and f_{tc} will contribute.
Here, f_s = modular ratio x f_{tc} and l_1 and l_2 are factors which depend on the geometric parameters.

Test	$f_{fc}.b.h' + A_h.f_s$	$f_{tc}.b.a + A_v.f_s$	Web strength is controlled by
(a)	$< A_h.f_{sy}$	$< A_v.f_{sy}$	**reinforcement**
(b)	$>$ or $> A_h.f_{sy}$ or $<$	$>$ or $> A_v.f_{sy}$ or $<$	**concrete**

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, l_1 and l_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.

$$(f_{tc}.b.h' + A_h.f_s) / (f_{tc}.b.a + A_v.f_s)$$
$$l_1 = l_2 = 1.$$

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 $f_{cu}.b.(h-h')/2$ 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_a at the support. For the evaluation of T_o, equation **(2)** is expressed as

$$V = ½ . (P_{u2} – f_{tc} . b.a – P_v) \quad (6)$$

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

$$T_o = \frac{V_a}{h'} \quad (7)$$

the force in the bar at the support, T_a, 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 whit using 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 I
MODEL SPECIFICATION

Code	Dimension BxHxT (mm)	Diagonal Reinforcement	
		Bar type	**Diameter Æ (mm)**
BK-1 BK-2	400x300x150 400x300x150	- -	- -
BD-1 BD-2	400x300x150 400x300x150	Deform Deform	10,0 10,0
BT-1 BT-2	400x300x150 400x300x150	CRT Bar CRT Bar	8,00 8,00

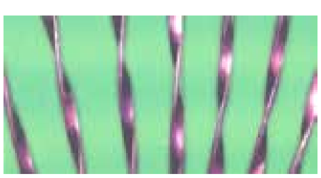


Fig. 5. Cold Rolled & Twisted Bar (CRT Bar)

VI. Result

TABLE II
STEEL STRENGTH

Speciment	Diameter (mm)	f_y (MPa)	f_u (MPa)	e (%)
CRT Bar	7,458	503,605	2044,943	11,517
Deform	10,0	528,393	783,041	25,581

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**).

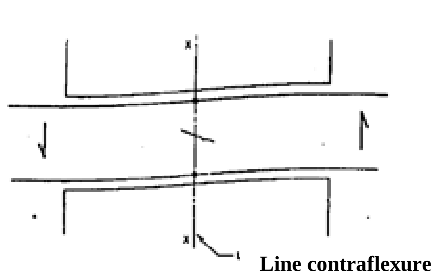


Fig. 6a. Early stage : flexural behavior

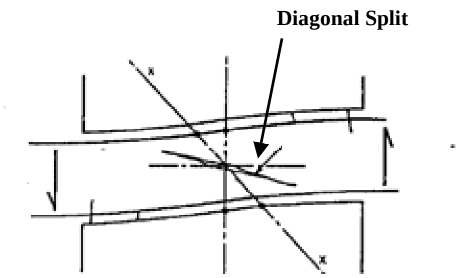


Fig. 6b. Diagonal splitting and rotation of the line of contraflexure

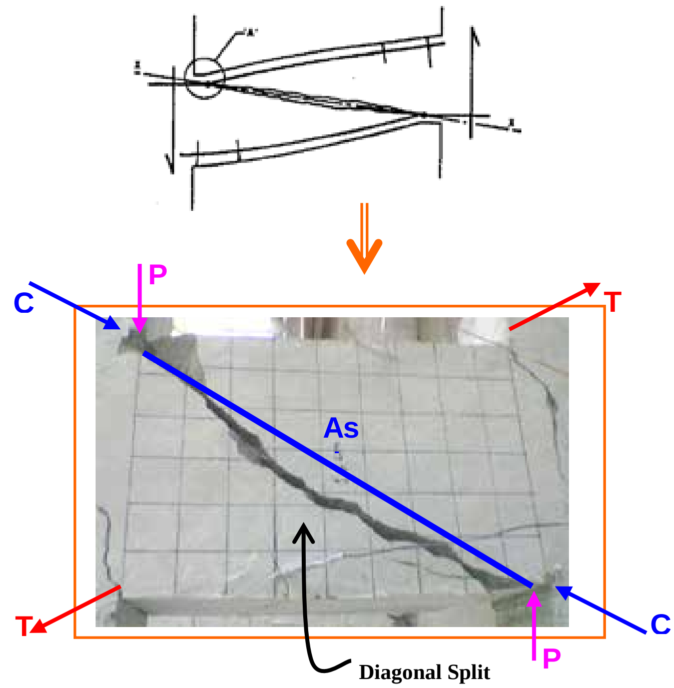


Fig. 6c. Final stage at failure : Final deformed shape

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 whit 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 III
CAPACITY AND SPLIT

Spec. Code	Split Wide (cm)	$P_{(first\ crack\ geser)}$ (kN)	P_{split} (kN)
BK	2,75	112,20	114,84
BD	1,35	128,70	135,96
BT	1,35	115,50	118,80

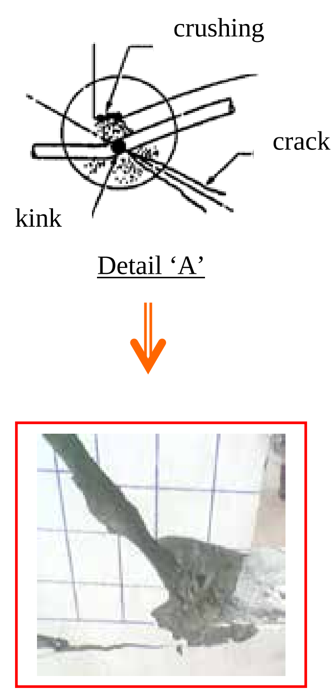


Fig. 7. Kink area

TABLE IV
COMPARISON BETWEEN THEORETICAL ANALYSIS WITH EXPERIMENTAL ANALYSIS

	BD-1	**BD-2**	**BT-1**	**BT-2**
$P_{u,theoretical}$ (kN)	178,648		94,646	
$P_{u,experiment}$ (kN)	125,40	135,96	121,44	116,16
mean	130,68		118,80	
$\frac{P_{u,\ eperiment}}{P_{u,\ theoretical}}$	0,73		1,26	

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

Experimental Result (BK)	f_c'	N/mm^2	21,073
	Mode of Failure	Shear, major diagonal crack, concrete and steel stresses seriously disturbed at the compression corners.	
	P_u, experimental	kN	114,84
Theoretical Result	f_{cu}	N/mm^2	26,341
	f_{tc}	N/mm^2	1,254
	P_u, flexural failure	kN	217,8410
	P_u, Shear failure	kN	112,1181
	Predicted mode of failure	Shear, diagonal splitting and crushing of concrete at the compression corners.	
	Ultimate load P_u, analysis	kN	112,1181
$\frac{P_u\text{, analysis}}{P_u\text{, experimental}}$	0,9763		

Referring to **Table. V**. two values for the ultimate strength, P_{u1} , based on the flexural mode of failure are given. The second row of P_{u1} value were calculate from equation **(1)** in which the flexural strength is based on the capacity of the main reinforcement alone.

The fifth row of P_{u1} values was extracted from equation **(5)**. These values represent the actual strengths based on the total horizontal bars in the cross section. It is clear that the flexural strengths are underestimated in the case of beams with the additional horizontal bars. Therefore, it is reasonable to take into account all the horizontal bars in calculating the flexural strength of the section.

Comparing the theoretical, P_{u1} and P_{u2}.. it is evident that in all cases, P_{u1}, is smaller. Hence the predicted mode of failure in all cases is shear or diagonal splitting with the crushing of the concrete at highly stressed compression corners.

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. P_u analysis / P_u 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 :

$$(m_D) = \frac{D_u}{D_y}.$$

Where, m_D= ductility

D_u= deflection at ultimate load

D_y= deflection at yield load

Deflection at yield (D_y) took at first crack moment. Deflection at ultimate (D_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 (m_D) in interval 1,5 to 3,5.

TABLE VI
DISPLACEMENT DUCTILITY

Spec. Code	**Ductility (m_D)**	m (mean)	**Improvement of ductility (%)**	
BK-1	1,644	1,630	-	
BK-2	1,616			
BD-1	1,936	1,957	20,06	9,269
BD-2	1,978			
BT-1	1,619	1,791	9,877	-
BT-2	1,962			

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.

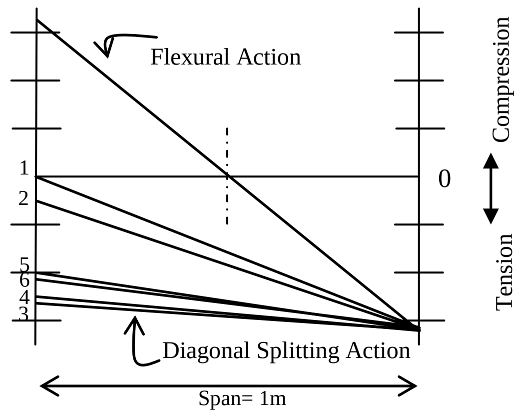


Fig. 8. Theoretical distribution of forces in the main bars

VII. Conclution

- § 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 of analysis 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 analysis result at coupling beams with reinforcement placing at diagonal direction with different type between deform type Æ10,0 mm with CRT Bar type Æ8,0 mm is : (a). Wide of diagonal split among usage both types of the steel bar do not show the differ far (b). Comparison of ductility value indicate that BD have value of ductility 9,27 % bigger compared to BT.
- § Ratio between P_u (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.

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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.