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An Investigation of Transfer Length in Prestressed Hollow Clay Masonry

Raghuveer SRIRAMULA
Postgraduate Student

Peter W. Kleeman
Honorary Associate
Department of Civil, Surveying and Environmental Engineering
University of Newcastle, NSW, 2308, Australia

Adrian W. Page
CBPI Professor in Structural Clay Brickwork, Dean, Faculty of Engineering
University of Newcastle, NSW, 2308, Australia

ABSTRACT

An experimental investigation to determine transfer length in prestressed hollow clay masonry is reported. Wallettes and stack bonded masonry prisms were constructed using extruded hollow clay brick units. Seven-wire standard prestressing strands of nominal diameter of 9.6 mm were installed in the cores of the hollow masonry, externally prestressed, the cores grouted, and after curing, the strands released. Three techniques were used to determine the transfer length; from the measurement of surface strains; from the measured tendon draw-in using existing empirical relationships; and from repetitive bending tests on the wallettes and prisms with each joint being loaded in turn until cracking occurred. The transfer lengths thus obtained were then compared with the transfer lengths calculated using recommended rules for prestressed concrete, and a simple expression for transfer length was derived.

INTRODUCTION

There is potential for the masonry construction industry to move towards industrialized walling systems because of the high cost of bricklaying, on-site construction difficulties, lack of quality control etc. Clay brick masonry is widely used as a veneer in low and medium rise residential and commercial buildings in Australia. Hollow clay masonry has been recently introduced and is being used in reinforced and prestressed masonry construction. Hence, there is the potential for the development of a prefabricated prestressed clay brickwork veneer system.

Prestressed masonry can be used in panelised construction as this technique imparts tensile strength to the masonry and helps significantly in resisting construction and erection stresses. Prestressing may be realised by either post-tensioning or pre-tensioning. A suitable method of prestressing for industrial (repetitive) construction could be the pre-tensioning system. With pre-tensioning, strands are typically installed in the cores of the hollow masonry, externally prestressed and the cores grouted. When the grout has cured, the strands are released, with the stress being transferred to the surrounding masonry by means of bond between the strands and the grout. One of the design parameters in pre-tensioning is the transfer length, that is, the length over which the prestress is developed.

A series of bending tests was carried out to investigate the transfer length in hollow clay masonry. Eight samples were tested; two of them were built as wallettes and six were prisms. The test results were used to calculate an average ultimate bond from which an equation for transfer length is derived. The results agree well with the ACI code provisions for transfer length for prestressed concrete.

PREVIOUS RESEARCH

There are no previously reported studies of transfer length for grouted hollow masonry. However, the factors influencing the transfer length in concrete construction were studied before choosing the variables for the investigation of transfer length in hollow masonry. Various factors such as the level of prestress, the mode of release of prestress (sudden/ gradual), the surface roughness of the tendon, etc influence the transfer length. From the tests of Holmberg and Lindgren on seven-wire strands, Hanson (1969) concluded that the gentle release of prestress reduced the transfer length in concrete by about 20 percent compared to sudden release. The transfer bond stress was almost independent of concrete strength between 10.3 to 34.5 MPa. It was concluded from a large number of tests that the source of bond was shrinkage rather than concrete strength. Hence, the bond strength is sensitive to all variables that effect shrinkage, with the concrete strength being of secondary importance. Stocker, M.F (1969). The high shrinkage of grout used in hollow clay masonry possibly improves the bond between strand and the grout. In spite of the large variation in measured values of transfer length, it is well established that the transfer length increases directly with strand diameter up to 15.7mm and remains practically unchanged with time. Buckner, C.D (1995). One of the influencing factors is surface rusting, with the transfer length reducing by about 40% for cases with significant surface rust. In the case of hollow clay masonry, the major differences from prestressed concrete systems are the use of grout instead of concrete and the fact that this grout is confined within the hollow core. Therefore, in this study the influence of different core sizes (90 mm and 110 mm size brick units), and grout strength (varying between 10 MPa and 50 MPa cylinder strength) were investigated. The remaining variables should have similar effects in both concrete and masonry systems.

EXPERIMENTAL PROGRAM

The transfer length was determined in the following three ways for each specimen:

- Initial draw-in
- Surface strains
- Bending moments

The initial draw-in method uses equations proposed for concrete systems in which draw-in and initial concrete strength are the required test data. The transfer length, determined from surface strains and the bending moments, is measured directly and no calculations are involved. The determination of transfer length from bending tests is a new technique and the results have been validated by comparing the results with the other two methods. The study was limited to the determination of transfer lengths using two different brick units and a range of grout strengths.

Materials

Two types of hollow clay units were used, one of 90 mm width the other 110 mm wide. In both cases, the units had two large cores, which allowed easy grout placement, with sufficient grout cover being provided to satisfy corrosion protection requirements. Both units were of high strength (characteristic compressive strength of 25 MPa and 26 MPa for the 90 mm and 110 mm units respectively). Details of the units are shown in Fig.1 (a). The prestressing steel was seven-wire standard strand of nominal diameter 9.6 mm, with a proof load of 102 KN, a breaking load of 105 KN and modulus of elasticity of 198 GPa. The primary function of the grout is to transfer the tensile force in the steel to the surrounding masonry. Hendry (1991) recommends that for reinforced and prestressed masonry the grout should be highly workable and self-compactible. The minimum compressive cylinder strength of grout should be between 10 to 15 MPa. In this work, the grout strength varied from 10 to 50 MPa, and the slump varied from 185 to 210 mm. The grout cylinders for compression tests were prepared using steel cylinder moulds while grouting the prisms in the laboratory. The constituents of the grout were Portland cement, 5 mm crushed stone, and sand. The cylinders were tested in compression on the same day as the release of prestress i.e. after 14 days of ambient curing. Type S-mortar i.e. 1:1:6 (Cement: Lime: Sand) by volume was used for laying the masonry.

Preparation of test specimens

Two wallettes (using 90 mm wide units) and six prisms (two of these were 110 mm wide units and the other were of 90 mm) were constructed as shown in Fig. 1 (b) and (c). The prisms were constructed in stack bond from eleven half brick units cut from full units. After curing for seven days, the prisms were moved (two at a time) to the pre-tensioning frame and the tendons were installed through the hollow cores as shown in Fig. 2(a). The tendons were tensioned (to about 70% of the yield strength) against the steel frame, and held at the top and bottom by anchorages, with the masonry remaining unstressed. The hollow cores were then filled with high slump grout. After 14 days of ambient curing, the tendons were released by gradually heating part of the exposed tendons with an oxy-acetylene torch. The bottom end of the tendon remained anchored against a steel channel (see Fig. 2 (b)). Hence the transfer length was developed at the top end only, termed the free end. The procedures for the two wallettes were similar, with only one core of the wallette being stressed and grouted.

Transfer length determined from surface strains (prisms only)

The bond that transfers the prestress from the strand to the surrounding body is termed the transfer bond, and exists only over the transfer length. The surface strain varies in the transfer length, but in other sections of the specimen essentially remains constant. Previous research has consistently demonstrated that the transfer bond stress occurs at a constant rate over the transfer length, and this assumption has been adopted here. With this assumption the strains in the transfer region would therefore vary linearly from zero at the free end to a maximum at the end of the transfer length. Thus, a straight line was drawn from zero through the data points. The length from zero to the point where the line through the data points cuts the line of constant strain represents the transfer length.

The masonry surface deformations were monitored while releasing the prestress using linearly varying displacement transducers (LVDTs) and potentiometers both connected to a data-logger. The arrangement of LVDTs and potentiometers for the prism specimens can be seen in Fig. 2(b) and Fig. 3 (c). Aluminium frames were used to hold the transducers in position and to maintain the gauge length (172 mm). As the prestress was released the load in the tendon at the anchorage and the corresponding masonry surface deformations were continuously monitored. The average strain $\varepsilon_{av.}$ was then calculated for each gauge length. For each specimen, readings at four different locations (over a constant gauge length as shown in Fig. 2(b)) were taken, and a graph of the net load in the tendon at the anchorage versus average strain was plotted as shown in Fig. 3(a). Another graph was plotted of the masonry average surface strains (maximum from the first graph) versus corresponding distance i.e. from free end to the middle of each frame. This graph was used to obtain the transfer length as shown in Fig. 3 (b). The surface strains were measured on three of the prism specimens (see Table 3). For each pair of prisms one prism was subjected to sudden release (SR) of the prestress (Prism numbers 2,3 and 4) and the other to gradual release (GR). For some of the specimens, the shocks associated with sudden release disturbed the frames holding the transducers and gave inconsistent results. The surface strain results for these specimens have been omitted.

Transfer length determined from bending test (prisms and wallettes)

In the bending test, each joint was loaded until the joint just opened. It was then unloaded and reloaded until the same joint reopened. The strength of the joint when it first cracks is a function of both the joint bond strength and the level of prestress. In the second stage, the bending strength of the cracked joint is a function of the prestress only, thus allowing the level of prestress to be determined. The general arrangement of the bending test is shown in Fig. 4 and Fig. 6. In each case, the cracking of the joint was determined from the readings from two LVDT's mounted across the joint under consideration on the tensile face of the prism. At each joint (numbered from 1 to 8 in Fig.4), the prism was loaded twice until the joint just opened and the applied load noted in each case.

Graphs were plotted of the applied moment versus the corresponding deformation as shown typically in Fig. 5(a) for the first stage, and Fig. 5(b) for the second stage. The cracking moment of each joint was obtained using an offset distance of 0.004 mm from the origin (as shown in Fig. 5 (a) and (b)) to provide more consistency in defining the cracking point. A third graph relating the moment that just causes the joint to open to the distance of the joint from free end was then plotted as shown in Fig. 5 (c). This idealized graph can be used to determine the transfer length. The result for one of the prisms was not consistent with the other results. This was attributed to the fact that the prism was cracked before grouting and the joint may therefore not have been completely closed. The results for this prism were therefore omitted.

Transfer length determined from Draw-In measurements

Considerable research has been carried out for prestressed concrete in relating the measured draw-in of the strand to the transfer length. Various investigators have suggested a range of empirical relationships. These are summarized in Table 6. Draw-in was measured with potentiometers fixed to the top of each prism as shown in Fig.2 (b). The transfer lengths were calculated from the measured draw-in using these relationships and compared (in Table 3) to the values obtained using the other methods.

DISCUSSION OF THE TEST RESULTS

In order to be able to compare the bending test results with the recommendations of various authors for prestressed concrete systems (see Table 5), the results have been adjusted, firstly for variation in the initial prestress and secondly, for differences between sudden release (SR) and gradual release (GR).

In the adjustment for initial prestress, it was assumed that transfer length is proportional to initial prestress. The values have been adjusted to a constant value of 1068 MPa, and are given in Table 1. To adjust for mode of release, the average value for gradual release (440 mm) is 18 percent less than the average transfer length for sudden release (536 mm). Transfer lengths adjusted to gradual release are given in the last column of Table 1. The transfer lengths obtained for the bending test (adjusted for gradual release) are compared with the recommendations from various sources in Table 2.

The shaded values are those in best agreement with the test results. The recommendations of the ACI (based on the proposals of Hanson and Kaar, and Shahawy et al) are a function only of the bar diameter and the level of prestress. With the exception of the AS 3600 relationship, the remaining relationships used in Table 2 include concrete strength in the equations. It can be seen that in the equations of Zia and Mostafa the transfer length is very sensitive to the concrete strength. The Mitchel et al and BS 5628 equations are consistent and relatively less sensitive to the concrete grade. The results from the current tests show that the transfer length is almost independent of grout strength. From Table 2, it can be concluded that the test results are in best agreement with the ACI code values.

Table 3 shows the transfer lengths calculated from the measured draw-in using the equations suggested by various authors (see Table 6). It can be seen that the bending test and surface strain test results best agree with the values calculated using the equation proposed by Uijl. The coefficients used in this equation are based on experimental and theoretical studies on hollow-core concrete slabs prestressed by seven-wire strands. The hollow-core concrete slabs are more likely to have behaved in a similar way to the hollow-cored masonry units of this study.

PROPOSED EQUATION FOR TRANSFER LENGTH

Previous research has consistently demonstrated that the transfer bond stress is constant over the transfer length. The ultimate bond stress can be calculated from the test results of transfer length if the bond is assumed constant over the transfer length. From equilibrium,

$$\text{Resisting bond force} = \text{effective prestressing force} = P_e.$$

$$4/3\ \pi\ d_b\ L_t \tau_{ub} = 0.78\ (\pi\ d_b^2/4)\ f_{se} \tag{1}$$

in which 4/3 is the coefficient used to calculate the actual perimeter of seven-wire strand, and 0.78 is the ratio between the actual cross sectional area and the nominal cross-sectional area of seven-wire strand. Where, f_{se} = effective prestress (MPa), τ_{ub} = ultimate bond stress (MPa), L_t = transfer length (mm) and d_b = diameter of the tendon. Substituting the observed value of transfer length into the above equation for each test gives the values of τ_{ub} given in Table 4. The average ultimate bond stress is 3.2 MPa. Substituting this value into the equilibrium equation above gives the relation,

$$L_t = f_{se} d_b/22. \tag{2}$$

The ACI code equation is derived using an average ultimate bond stress of 2.76 MPa. The average ultimate bond stress from the current test results was 3.2 MPa, an increase of 16% over the ACI code provisions. The reasons for the increase of bond are likely to be the result of shrinkage of the grout, confining effect of the hollow core (due to the difference in elastic properties between brick masonry and the grout) and the strand surface condition.

CONCLUSIONS

A limited study of transfer length in hollow clay masonry has been described and a simple expression for predicting transfer length derived. The results show that the transfer length in grouted hollow clay masonry is similar to that in concrete systems and agrees closely with the ACI code provisions. Although the compressive strength of the grout varied between 49 MPa and 11 MPa, there was no significant influence of grout strength on transfer length. The ACI code equation was derived using an average ultimate bond stress of 2.76 MPa. Buckner, C.D (1995). The average ultimate bond stress from these tests was 3.2 MPa, an increase of 16%. The reasons for the increase of bond are considered to associated with the shrinkage of the grout, the confining effect of the hollow core and the strand surface condition.

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REFERENCES

AS 3600 –1994. SAA Concrete Structures Code, Standards Association of Australia.

Buckner, C.D. 1995. A Review of Strand Development Length for Pre-tensioned Concrete Members, PCI journal, V 40, n 2, pp 84-105.

Balazs, GL. 1993. Transfer Length of Prestressing Strand as a Function of Draw-In and Initial Prestress. PCI journal, V 38, n 2, pp 86-93.

Hanson, NW. 1969. Influence of surface roughness of prestressing strand on bond Performance. PCI journal,Vol 14, n 1, pp 32-45.

Hendry, AW. 1991. Reinforced and Prestressed Masonry, Longman Scientific and Technical, Longman Group UK Limited.

Schultz, AE and Scolforo, MJ. 1992, Engineering Design Provisions for Prestressed Masonry: Part 2: Steel Stresses and Other Considerations. The Masonry Society. V 10, n 2, pp 48-60.

Stocker, MF and Sozen MA. 1969. Investigation of Prestressed Reinforced Concrete Highway Bridges. Part IV. Bond characteristics of Prestressing strand.

Zia, P., and Mostafa, T. 1977. Development Length of Prestressing Strand. PCI journal, V 22, n 5, pp 54-65.

Table 1. Transfer lengths (mm) from bending tests.

Specimen	Type of release	Grout mean strength (MPa)	f_{si} (Mpa)	Bending test result	Adjusted for constant prestress	Final transfer lengths (mm) *
Wall # 1	GR(90)	49	1071	440	439	440
Wall # 2	GR(90)	49	1062	438	440	438
Prism # 1	GR(90)	17.9	1068	440	440	440
Prism # 2	SR(90)	17.9	1027	530	551	435
Prism # 3	SR(90)	32.9	1043	516	528	423
Prism # 4	SR(110)	10.7	1048	520	530	426
Prism # 5	GR(110)	10.7	1210	498	440	498

* The transfer lengths assuming an 18% reduction for the SR case.

Note: GR= Gradually Released, SR= Suddenly Released, f_{si} = Initial Prestress.

Table 2: Transfer lengths (mm) proposed by various authors.

Speci-men	Grout strength (MPa)	f_{si} (MPa)	ACI code	Zia & Mostafa	Shahawy et al.	Mitchel et al.	BS 5628	AS 3600	From Bending Test	Comments
Wall # 1	49	1071	472	199	497	323	328	576	440	GR (90)
Wall # 2	49	1062	468	196	493	320	328	576	438	GR (90)
Prism # 1	17.92	1068	471	742	495	532	542	576	440	GR (90)
Prism # 2	17.92	1027	452	709	476	512	542	576	530	SR (90)
									435	18% less
Prism # 3	32.92	1043	460	340	484	383	400	576	516	SR (90)
									423	18% less
Prism # 4	10.7	1048	462	1294	486	676	701	576	520	SR (90)
									426	18% less
Prism # 5	10.7	1210	533	1513	561	781	701	576	498	GR (110)

Table 3: Transfer length (mm) from initial draw-in using equations of various authors.

Transfer length from initial draw-in								Test results	
Specimen	Draw-in (mm)	Guyon		Polish researchers	Uijl	Balazs		From Surface Strains	From Bending Moments
		∝ =2	∝=3	∝ =2.86	∝ =2.46	I	II		
Wall # 1	0.96	355	532	508	437	536	487		440
Wall # 2	0.95	354	531	507	436	533	485		438
Prism # 1	0.95	352	527	503	432	887	563	430	440
Prism # 2	1.19	459	689	657	565	806	659	530	530
Prism # 3	1.17	444	666	635	546	607	591		516
Prism # 4	1.13	428	643	613	527	1077	685		520
Prism # 5	1.15	376	564	538	463	1240	652	500	498

Table 4: Comparison of Transfer lengths (mm).

Details	From Strain	From BM	* L_t	ACI code	Uijl	τ_{ub} (MPa)	$L_t = f_{se}d_b/22$	Comments
Wall # 1		440	440	472	437	3.2	445	GR (90)
Wall # 2		438	438	468	436	3.2	441	GR (90)
Prism # 1	430	440	440	471	432	3.2	443	GR (90)
Prism # 2	530	530	435	452	565	3.2	427	SR (90)
Prism # 3		516	423	460	546	3.3	433	SR (90)
Prism # 4		520	426	462	527	3.2	435	SR (110)
Prism # 5	500	498	498	533	463	3.2	503	GR (110)

* Transfer lengths for gradual release (transfer lengths for sudden release have been reduced by 18 percent).

Table 5: Equations for transfer length proposed by various authors:

Author	Proposed equation for transfer length
Current AASHTO / ACI: (Buckner CD, 1995)	$L_t = f_{se}d_b/20.7 \approx 50d_b$
Shahawy et al: (Buckner CD, 1995)	$L_t = f_{si}\, d_b/ 20.7$
Mitchel et al: (Buckner CD, 1995)	$L_t = 0.0483\, f_{si}\, d_b\sqrt{20.7/ f_{ci}}$
Zia & Mustafa: (Zia and Mostafa, 1977)	$L_t = [1.5(f_{si} / f_{ci})\, d_b] - 116.8$
BS 5628: (Schultz AE, et al, 1992)	$L_t = K_t\, d_b\sqrt{f'_c}$ $K_t = 239$, for seven-wire strand
AS 3600: (Australian Standards, 1994)	$L_t = 60d_b$ (For seven-wire strand

Table 6: Transfer length from initial draw-in: (Balazs GL, 1993).

Guyon:	$L_t = \propto S / \in_{si}$. Where $\propto = 2$, for constant bond stress distribution $\propto = 3$, for linear bond stress distribution
Polish researchers:	$\propto = 2.86$, from test results
Uijl: Balazs, GL:	$\propto = 2.46$, from experimental and theoretical studies on hollow cored slabs. (I) $L_t = 3.47\, f_{si} / (\sqrt{f_{ci}}\sqrt{S})$ and (II) $L_t = 111\, S^{0.625} / (f'_{ci}{}^{0.15} \in_{si}{}^{0.4})$

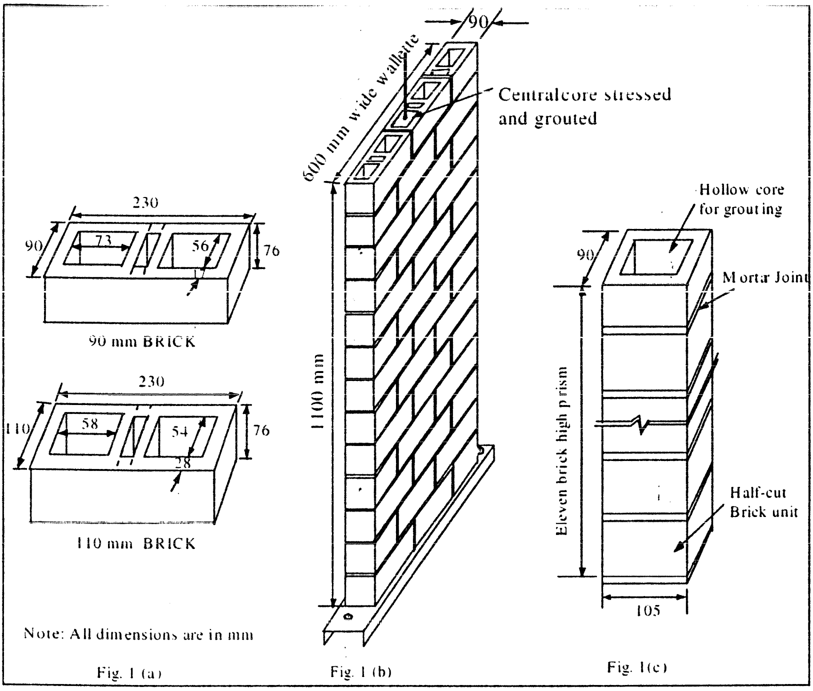


Fig. 1 (a)   Fig. 1 (b)   Fig. 1(c)

Fig. 1. Details of the specimen

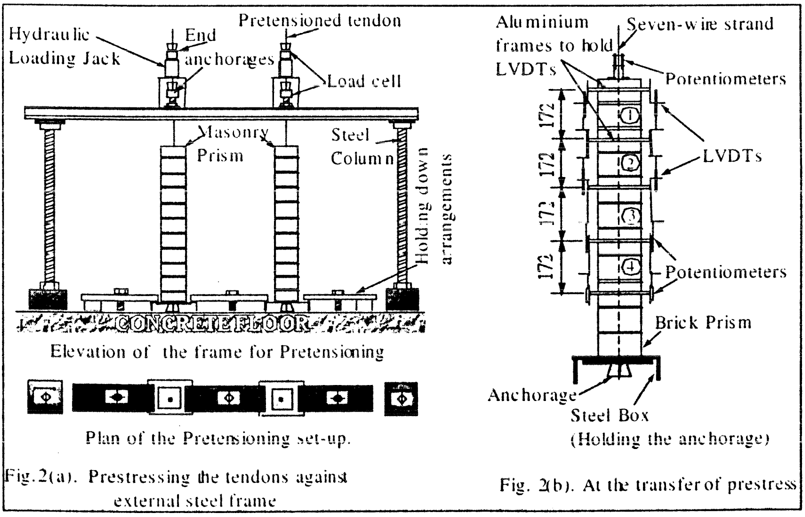


Fig.2(a). Prestressing the tendons against external steel frame

Fig. 2(b). At the transfer of prestress

Fig. 2. Prestressing Details

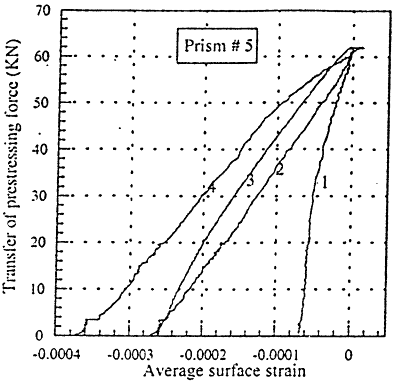


Fig. 3 (a). Typical plot of Load versus average surface strains.

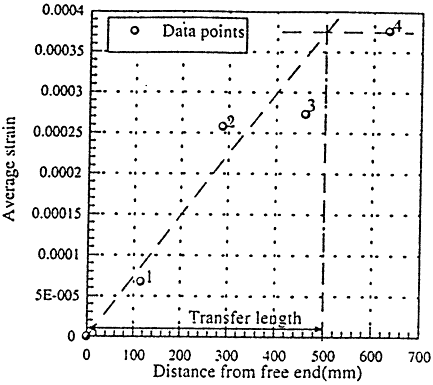


Fig. 3 (b). Typical plot of transfer length derived from average surface strain

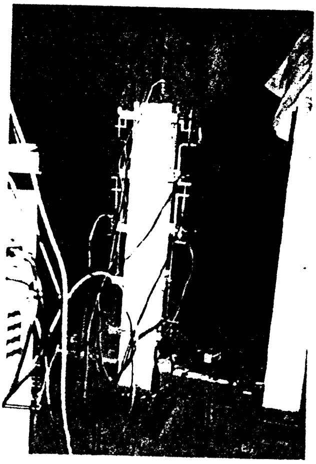


Fig. 3 (c). Arrangement of LVDT's to measure the surface deformations

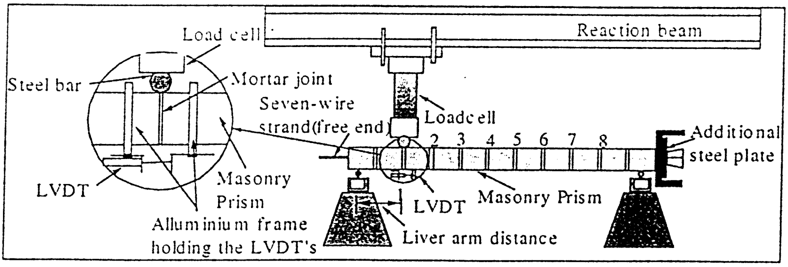
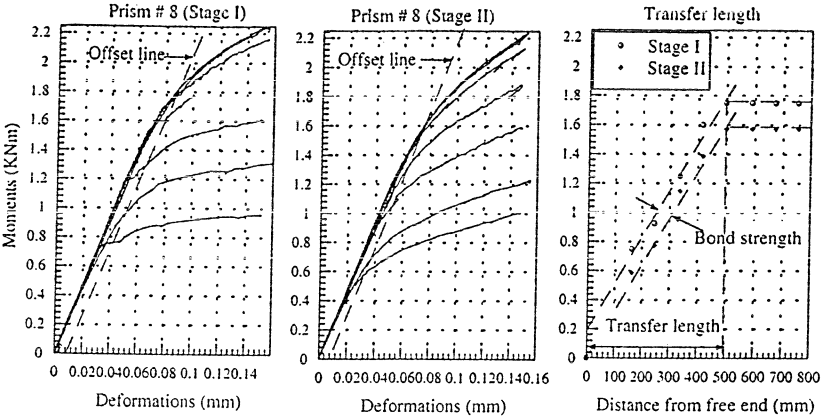


Fig. 4. Idealised arrangement for bending test.



(a). First stage cracking (b). Second stage cracking (c) Transfer length

Fig. 5. Typical plot of the transfer length from cracking moments

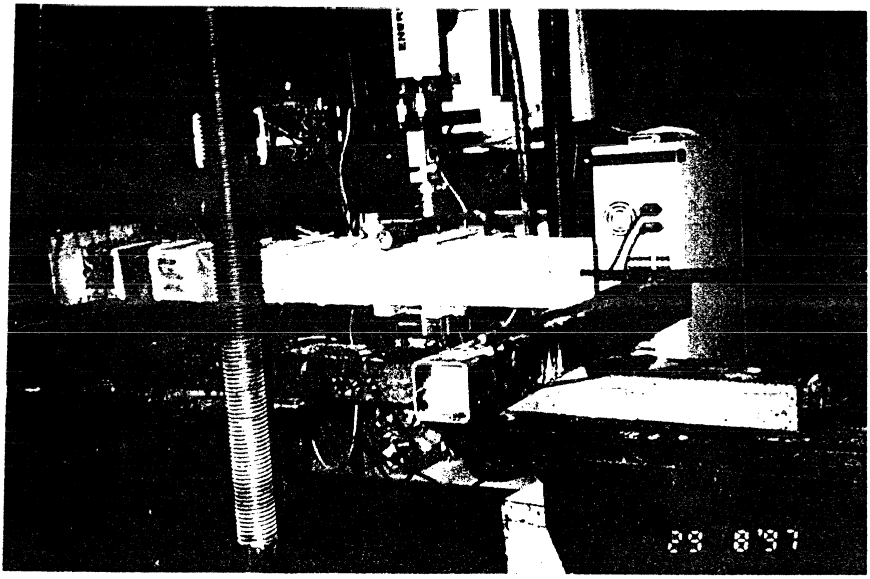


Fig. 6. Three point bending test arrangement