NISTIR 6565

Tensile Strength of an Interlocking Composite Connection

Dat Duthinh

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Structures Division
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U.S. Department of Commerce
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ABSTRACT

Twenty four tests of an interlocking fiber-reinforced polymer (FRP) connection show that, although the connection is much weaker than the theoretical strength of the panel under the same type of load (in-plane tension transverse to the main reinforcement direction), it is well designed and performs its function satisfactorily. The tensile strength of the connection exhibits the least variability in the interlocked, no bond configuration. Adhesive bonding adds significantly to the strength of this interlocking joint. Spreading adhesive on both mating faces in the absence of an interlocking toggle produces a more complete bond area and a thicker bond line, resulting in significantly higher connection strength than if the adhesive is deposited on only one face and a toggle is used. Infills of various stiffness have no effect on strength and the toggle shows no sign of damage at connection failure.

Keywords: adhesive, bond, composite, connection, fiber-reinforced polymer, FRP, interlocking, joint, panel, tensile strength.

ACKNOWLEDGMENT

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DISCLAIMER

Contents

Tensile Strength of an Interlocking Composite Connection

1. Introduction

FRP (fiber-reinforced polymer) structural members are increasingly used in civil engineering applications, such as in bridge decks and girders. One promising application is in residential housing, where FRP panels can be assembled quickly on site, without the need for additional framing. The speed of erection is particularly important for emergency and military shelters. Further advantages are the light weight of the material and the possibility of fabricating standardized panels and connections in the factory, thus potentially leading to lower cost and improved quality control.

This work evaluates the tensile strength of a particular type of interlocking joint used to assemble double-skinned panels (Fig. 1). The panels can be used in walls, floors and roofs of shelters and are assembled by driving a toggle into the jaws of the end cells (Head and Churchman, 1989). Foam can be injected into the cells formed by the panel skins and stiffeners for insulation. For permanent structures, adhesive bonding can also be used in addition to mechanical interlocking. If no adhesive is used, disassembly and reuse are possible.

Several interlocking composite joints are commercially available (Duthinh, 2000). However, they all are proprietary designs and their performance is not generally known to the engineering community. To facilitate the use of this promising technology, NIST is undertaking a series of tests to measure the performance of this type of joint and to make the results available in the public domain. It is our hope that more companies will participate in this program, which, in conformance with NIST mission, aims to serve the public and the industry.

2. Panel Tensile Tests

Under wind or earthquake loads, the external walls and internal partitions of a house can act as shear walls, i.e., they resist in-plane, biaxial, diagonal tension and compression. Crucial to this function is the performance under tension of the connections between the wall panels. For this purpose, we tested 24 specimens 152 mm (6 in) wide in tension (Width is the dimension perpendicular to the plane of Fig. 4. See Tables 1m for SI units and 1 for US customary units). Of these, 13 experiments tested the connection in a "single" configuration, and 11 in a "double" configuration.

The "single" configuration, shown in Fig. 2, was intended to measure the effect of various infills on the performance of the connection. Infills of various stiffness, such as foam, high-strength mortar, or air (no infill), could affect the resistance of the cell to gross distortion, thus influencing the tendency for the connection to disengage and fail. Two cells, including one end cell, were attached to a steel fixture by the FRP toggle. The steel fixture was custom-made to exactly conform to the toggle. The lower cell had a thin aluminum liner that served to spread the load and minimize stress concentration and distortion of the cell. Tension was applied via a thick steel plate inserted into the lower cell and its liner and bolted at its ends to a fixture attached to the testing machine. The stiff steel plate ensured a fairly uniform load distribution over the length of the cell (or width of the specimen). This set-up worked well and failure always occurred at the FRP connection. The aluminum liner thus prevented possible premature failure due to load application.

Figure 3 shows a "single" test with foam infill. Note the delamination cracks due to radial normal tension caused by straightening out of the right lip. (Lips refer to the cantilevered parts of the panel in contact with the toggle, whereas jaws refer to the entire face of the end cell).

The "double" tests were intended to measure the performance of the connection in the configuration used in practice. The set-up (Fig. 4) involved two upper cells and an upper load fixture that were the mirror image of the (lower) cells and load fixture shown in Figs. 2 and 3. Three possible configurations were tested: interlock only, adhesive bond only, and both interlock and bond. Figs. 5 and 6 show details of the "double" tests, where cracks are typical of the failures observed. All panel tensile tests were conducted at a loading rate of 0.76 mm/min (0.03 in/min).

For the interlocked and bonded specimens, we followed the manufacturer's bonding recommendations: First, we lightly sanded and wiped the mating surfaces clean. Next, we applied to *only one* of the two pieces to be joined a 3 mm (1/8 in) diameter bead of adhesive in each of two grooves on the sides of the toggle cavity. We then aligned and mated the two parts together and inserted the toggle, making sure that no adhesive was applied to the toggle or toggle cavity. The specimen was left undisturbed to cure for at least 16 hours. For the bonded only specimens, the procedure was similar, except that adhesive was applied to *both* mating surfaces, which were subsequently clamped together.

3. Data analysis

"Single" tests

For the n = 13 "single" tests, results for the 152 mm (6 in) specimens are as follows:

- Mean strength: 1.70 kN (381 lbf)
- Standard deviation: σ = 207 N (45 lbf)
- Standard error: $\sigma / \sqrt{n}$ = 57.4 N (12.4 lbf)
- Insert (air, foam or mortar) has no significant effect (Fig. 7, and Section 6, Note 3).

"Double" tests

The "double" tests showed that the tensile strengths corresponding to bond only, interlock only, or both interlock and bond were significantly different (Fig. 8, and Section 6, Notes 3 and 4). In addition, the load deflection curves showed clearly a decrease in stiffness when the applied tension overcame the preload exerted by the toggle and the jaws separate (Tables 1m, 1 and Fig. 10m, 10). This change in stiffness thus provided a means to measure the preload. For the three interlocked only specimens (#25-27), the mean preload exerted by the toggle was 633 N (142 lbf). Compared to the "single" tests (Figs. 9m, 9), the interlocked only, "double" tests exhibited a surprisingly lower mean strength and small spread (tests 25-27 have a mean strength of 1.39 kN or 312 lbf and a standard deviation of 40 N or 9.0 lbf). Once of the jaws have separated, we expected the "double" tests to show the same behavior and ultimate strength as the "single" tests.

Connections that were both bonded and interlocked exhibited a surprisingly lower strength (mean 4.42 kN or 994 lbf of tests 22-24) than those that were bonded only (mean 8.68 kN or 1950 lbf of tests 29-31). As mentioned above, the bonded only specimens had adhesive spread on both mating faces, whereas the bonded and interlocked specimens had adhesive spread on one face only. Also, the preload exerted by the toggle squeezed out all but a thin layer of adhesive, whereas in the bonded only cases, clamping was weaker, resulting in a thicker bond line. All the bonded only specimens (#29, 30, 31) achieved 100 % adhesive coverage of the jaw area. Connection failure occurred by tension failure of the FRP jaws near their surface, leaving a dull, fibrous surface, and not in the adhesive or at the adhesive-FRP interface. Only one of the interlocked and bonded specimens (#32) had similar adhesive coverage and FRP failure, and it achieved a strength comparable to that of the bonded only specimen. The others (#22, 23, 24, 28) had adhesive coverage ranging from 50 % to 80 % and failure included regions of adhesive-FRP interface failure, adhesive through-thickness failure as well as FRP near surface tensile failure. Bond failure for specimen 28, for example, was by FRP near surface tensile failure over 90 % of the bonded area. However, this bonded area only covered 60 % of the jaw surface, and caused a reduction in strength of 60 % compared with specimen 32.

It is noteworthy that failure of the bonded specimens (Figs. 11m and 11) was not necessarily more brittle than that of interlocked (Figs. 10m and 10) or interlocked and bonded specimens (Figs.12m and 12). Bonded only specimens did not fail abruptly after the first peak load, but sometimes achieved a second peak of about the same magnitude after considerable deformation due mostly to gross distortion of the cells rather than strain in the adhesive (Figs. 11m and 11).

Coupon tests

Four longitudinal coupons (305 mm × 33 mm or 12 in × 1.3 in) and seven transverse coupons (70 mm × 14 mm or 2.75 in × 0.57 in) cut from the panel walls were tested in tension. The coupon ends and gage length were of the same width, and the ends were of triple thickness, bonded with the adhesive recommended by the manufacturer. The mean strengths measured were about 1 σ (one standard deviation) lower for transverse strength and 1.5 σ lower for longitudinal strength than the manufacturer's values (Tables 2 and 3). The slightly lower strength than the specified values should not be a cause for alarm as these tests were not standard ASTM tests, but rather were intended to be rapid tests to verify that the material was indeed what it was supposed to be.

4. Future work

Future tests will include in-plane and out-of plane shear and bending. Compression tests are not planned, because compression should not be a problem for this particular connection, as global buckling of the panel or local buckling of its walls would occur before gross distortion of the jaws due to compression.

5. Conclusions

The tensile strength of the toggle connection exhibited the least variability in the interlocked only, "double" configuration. Adhesive bonding added significantly to the strength of this interlocking joint. Spreading adhesive on both mating faces in the absence of a toggle produced a more complete bond area and a thicker bond line, resulting in significantly higher connection strength than if the adhesive was deposited on only one face and a toggle was used. Infills of various stiffnesses had no effect on strength and the toggle showed no sign of damage at connection failure. Although the toggle connection is much weaker than the theoretical strength of the panel under the same type of load (in-plane tension transverse to the main reinforcement direction), it is well designed and performs its function satisfactorily.

6. Uncertainty and statistics:

Note 1, load uncertainty: According to the latest calibration sheet of the testing machine, for the relevant range of loads, 1070 N to 10 700 N (240 lbf to 2400 lbf), the load displayed by the testing machine is less than 0.3 % lower than the calibrating device. The maximum load was recorded directly by the testing machine, whereas other peak loads were read at a scanning rate of 10 Hz. The scanned maximum load was less than 18 N (4 lbf) lower than the machine load.

With one exception, the widths of the specimens were within 1.6 mm (1/16 in) or 1 % of the intended width of 152 mm (6 in). The exception was specimen 28, which had a width of 149 mm (5 7/8 in). Results of test 28 were multiplied by 152/149 = 1.02 for consistency with the other tests. Cumulative uncertainty for load per unit width is therefore estimated to be about 1.5 %.

Note 2, displacement uncertainty: Observations about stiffness and ductility relied on displacements, which were measured directly by the loading machine to control its loading rate. These measures were usually not precise enough for small displacements that occurred in coupon tests for example, but were adequate for large displacements caused by gross distortion of the cross-section, as occurred here. Nevertheless, observations based on displacements should only be used for comparison of similar test configurations and not in an absolute sense.

Note 3, *F*-test: Figures 7 and 8 are one-way, unbalanced ANOVA (analysis of variance) tables. Let y_{ij} be the measured connection strength, where subscript i denotes the test configuration, j the test replication number, n_i the total number of replicates per configuration, I the total number of test configurations and N the total number of tests. The components of variance are as follows:

Source	Degrees of freedom	Sum of squares
Mean	1	$N\,\bar{y}^2$
Effect (Columns)	$I-1$	$\sum_{i=1}^{I} n_i\,(\bar{y}_i - \bar{y})^2$
Error	$N-I$	$\sum_{i=1}^{I}\sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2$
Total	N	$\sum_{i=1}^{I}\sum_{j=1}^{n_i} y_{ij}^{\,2}$

The mean square *(MS)* is the ratio of the sum of squares over the corresponding number of degrees of freedom. The F-test (likelihood ratio) for the effect is the ratio:

$$\frac{\textit{mean square for the deviations among the groups MS (effect)}}{\textit{mean square for the deviations within the groups MS (error)}}$$

The further the effects are from zero, the further the F-statistic is from one. This is measured by the probability that the value of $F_{(I-1);(N-I)}$ is greater than the ratio defined above.

Note 4, *t* test: In Fig. 8, the averages of the connection strength for various configurations are also compared. Let x_i and y_i be the measurements, repeated n and k times respectively, for two configurations. We are interested in knowing if the difference in the means, $m_x - m_y$, estimated by the differences in the averages $\bar{x} - \bar{y}$ would be zero. If s_x^2 and s_y^2 denote the unbiased estimates of variance for x_i and y_i, then a pooled estimate of variance can be defined:

$$s_p^2 = \frac{(n-1)\,s_x^2 + (k-1)\,s_y^2}{n+k-2}$$

The quantity $t = \dfrac{(\bar{x}-\bar{y})-0}{\sqrt{\dfrac{n+k}{nk}}\,s_p}$ is distributed as Student's t with the number of degrees of freedom $\nu = n + k - 2$. The table gives the probability that $m_x = m_y$.

7. References

Duthinh, D. (2000), "Connections of Fiber-Reinforced Polymer (FRP) Structural Members: a Review of the State of the Art," NISTIR 6532, NIST, Gaithersburg, MD.

Head, P.R. and Churchman, Q.E. (1989), "Design, Specification and Manufacture of a Pultruded Composite Construction System." *Proc., BPF Symposium on Mass Production Composites*, Imperial College, London, Sep., pp. 117-162.

Table 1m Panel Tensile Tests

Test	Max N	Stiffness1 N/mm	Stiffness2 N/mm	Preload N	Couple	Infill	Toggle	Bond	Peak1 N	Peak2 N	Peak3 N	Peak4 N	Peak5 N
9	1416	773			single	no	yes	no	1416	1336			
10	1546	786			single	no	yes	no	1546				
11	1594	940			single	no	yes	no	1422	1594	1219	1199	
12	1716	823			single	no	yes	no	1716				
13	1840	1281			single	no	yes	no	1308	1840	1127		
14	1545	836			single	mortar	yes	no	1545	1114	747	819	
15	1888	1182			single	mortar	yes	no	1362	1450	1888	1734	1532
16	1584	874			single	mortar	yes	no	1584	1344			
17	1946	833			single	mortar	yes	no	1293	1946			
18	1471	880			single	foam	yes	no	1285	1471			
19	1827	949			single	foam	yes	no	1590	1827			
20	1566	737			single	foam	yes	no	1566	1492	1368		
21	2099	1144			single	foam	yes	no	1873	2099			
Mean 9-21	1695	926							1501				
St.Dev.9-21	207	171							175				
22	3626	2505			double	foam	yes	yes	3626	3392			
23	4236	2396			double	foam	yes	yes	4236	3985			
24	5401	1760			double	foam	yes	yes	5401	4593			
28	2993	648			double	foam	yes	yes	2993				
32	7349	2821			double	no	yes	yes	7349	6522			
Mean 22-24	4421	2220							4421				
St.Dev.22-24	902	402							902				
M 22-24,28,32	4721	2026							4721				
SD 22-24,28,32	1717	861							1717				
25	1426	2049	554	701	double	foam	yes	no	1423	1426	1328		
26	1346	2524	394	709	double	foam	yes	no	1261	1346	1334		
27	1390	1276	505	489	double	foam	yes	no	1167	1390	1220		
Mean 25-27	1387	1949	484	633					1284	1387	1294		
St.Dev.25-27	40	630	82	124					130	40	64		
29	10242	3355			double	no	no	yes	10242				
30	7071	2803			double	no	no	yes	7071	6967			
31	8732	3295			double	no	no	yes	8732	5387			
Mean 29-31	8682	3151							8682				
St.Dev.29-31	1586	303							1586				

Table 1 Panel Tensile Tests

Test	Max lbf	Stiffness1 lbf/in	Stiffness2 lbf/in	Preload lbf	Couple	Infill	Toggle	Bond	Peak1 lbf	Peak2 lbf	Peak3 lbf	Peak4 lbf	Peak5 lbf
9	318.4	4413			single	no	yes	no	318.4	300.3			
10	347.6	4491			single	no	yes	no	347.6				
11	358.4	5371			single	no	yes	no	319.6	358.4	274.1	269.5	
12	385.8	4700			single	no	yes	no	385.8				
13	413.7	7316			single	no	yes	no	294.0	413.7	253.4		
14	347.4	4777			single	mortar	yes	no	347.4	250.4	168.0	184.2	
15	424.5	6750			single	mortar	yes	no	306.3	325.9	424.5	389.8	344.4
16	356.2	4993			single	mortar	yes	no	356.2	302.2			
17	437.6	4759			single	mortar	yes	no	290.8	437.6			
18	330.6	5025			single	foam	yes	no	288.8	330.6			
19	410.7	5421			single	foam	yes	no	357.5	410.7			
20	352.1	4210			single	foam	yes	no	352.1	335.5	307.5		
21	472.0	6534			single	foam	yes	no	421.1	472.0			
Mean 9-21	381.2	5289							337.4				
St. Dev. 9-21	44.7	976							39.4				
22	815.2	14308			double	foam	yes	yes	815.2	762.6			
23	952.3	13681			double	foam	yes	yes	952.3	895.9			
24	1214.2	10051			double	foam	yes	yes	1214.2	1032.7			
28	672.9	3700			double	foam	yes	yes	672.9				
32	1652.3	16109			double	no	yes	yes	1652.3	1466.3			
Mean 22-24	993.9	12680							993.9				
St. Dev. 22-24	202.7	2298							202.7				
M 22-24, 28, 32	1061.4	11570							1061.4				
SD 22-24, 28, 32	386.0	4919							386.0				
25	320.5	11700	3162	157.5	double	foam	yes	no	320.0	320.5	298.6		
26	302.5	14414	2252	159.4	double	foam	yes	no	283.5	302.5	299.8		
27	312.4	7286	2883	110.0	double	foam	yes	no	262.3	312.4	274.2		
Mean 25-27	311.8	11133	2766	142.3					288.6	311.8	290.9		
St. Dev. 25-27	9.0	3598	466	28.0					29.2	9.0	14.4		
29	2302.7	19159			double	no	no	yes	2302.7				
30	1589.7	16010			double	no	no	yes	1589.7	1566.4			
31	1963.2	18817			double	no	no	yes	1963.2	1211.2			
Mean 29-31	1951.9	17995							1951.9				
St. Dev. 29-31	356.6	1728							356.6				

Table 2 Longitudinal Coupon Tests

Test	Length		Width		Thickness		Strength	
	mm	in	mm	in	mm	in	MPa	ksi
48	171	6.75	34.7	1.365	3.05	0.120	525.3	76.18
49	171	6.75	33.9	1.334	2.79	0.110	524.4	76.05
50	171	6.75	33.9	1.333	2.79	0.110	522.9	75.84
51	171	6.75	33.5	1.317	3.18	0.125	555.7	80.60
Mean							532.1	77.17
St. dev.							15.8	2.29
Manuf. Specs							556	80.6

Table 3 Transverse Coupon Tests

Test	Length		Width		Thickness		Strength	
	mm	in	mm	in	mm	in	MPa	ksi
41	44.5	1.75	14.9	0.587	3.00	0.118	62.9	9.12
42	44.5	1.75	14.9	0.587	3.00	0.118	59.2	8.58
43	44.5	1.75	14.1	0.555	2.97	0.117	42.9	6.22
44	44.5	1.75	13.7	0.538	3.00	0.118	54.1	7.84
45	44.5	1.75	14.8	0.584	3.00	0.118	50.3	7.30
46	44.5	1.75	14.6	0.575	3.00	0.118	47.3	6.86
47	44.5	1.75	14.1	0.554	3.00	0.117	53.4	7.74
Mean							52.9	7.67
St. dev.							6.3	0.91
Manuf. Specs							58.5	8.48

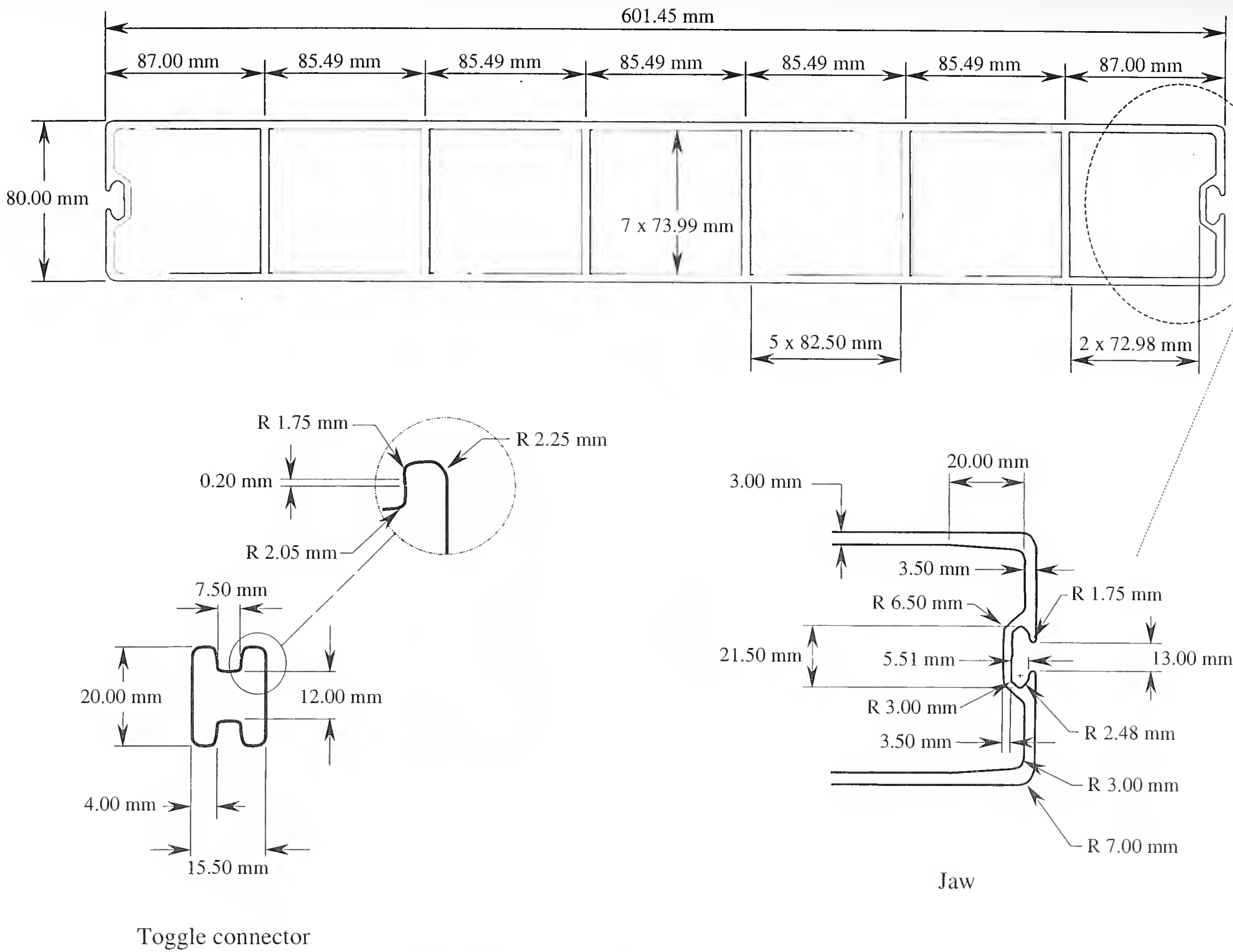


Fig. 1 Panel and Toggle Connector

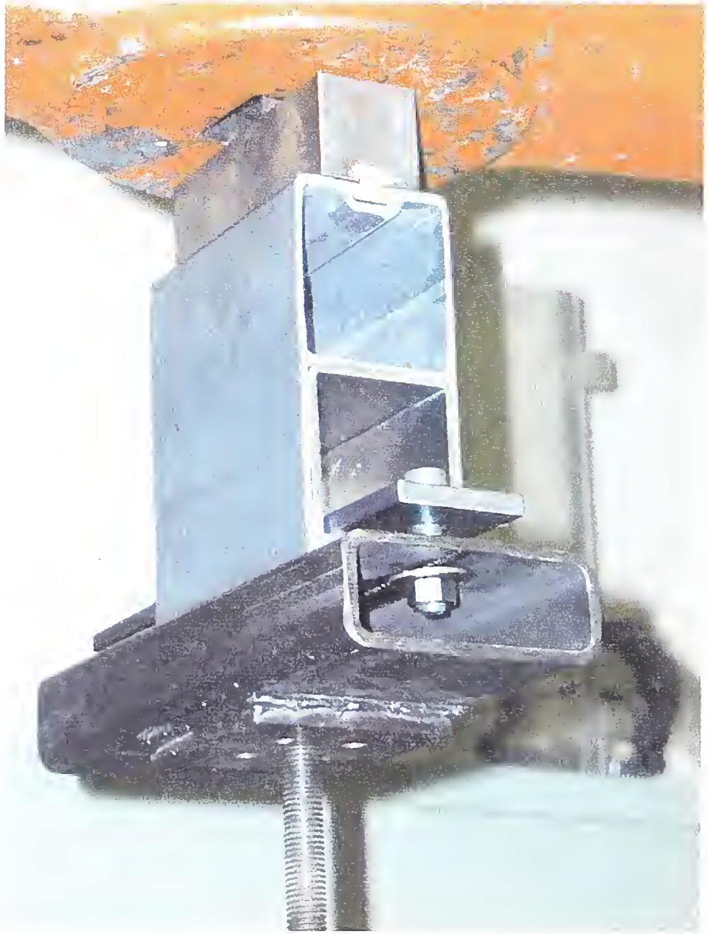


Fig. 2 “Single” tensile test with no infill

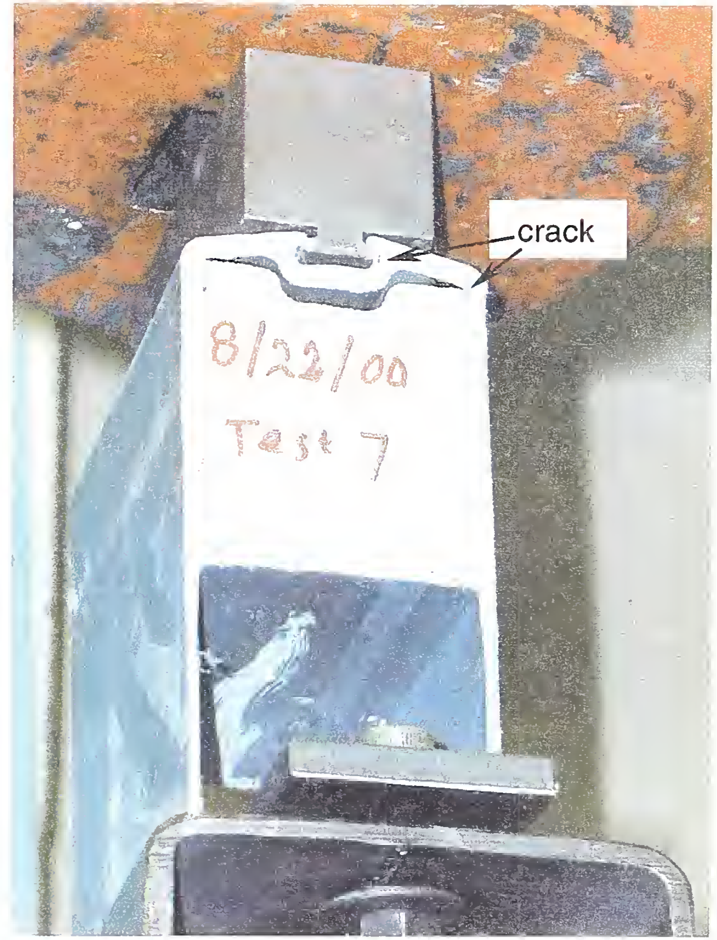


Fig. 3 “Single” tensile test with mortar infill

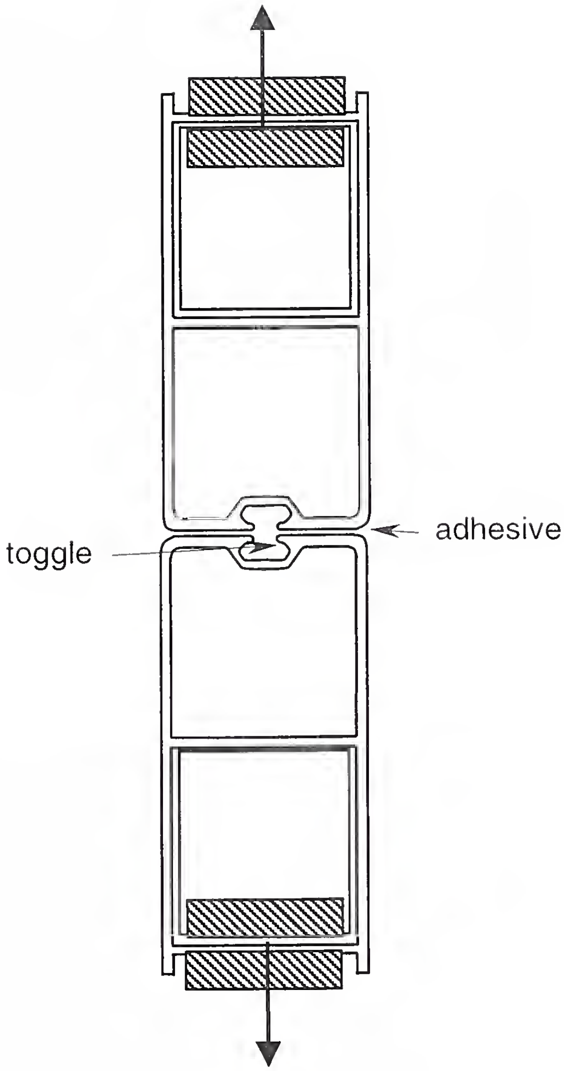


Fig. 4 "Double" test

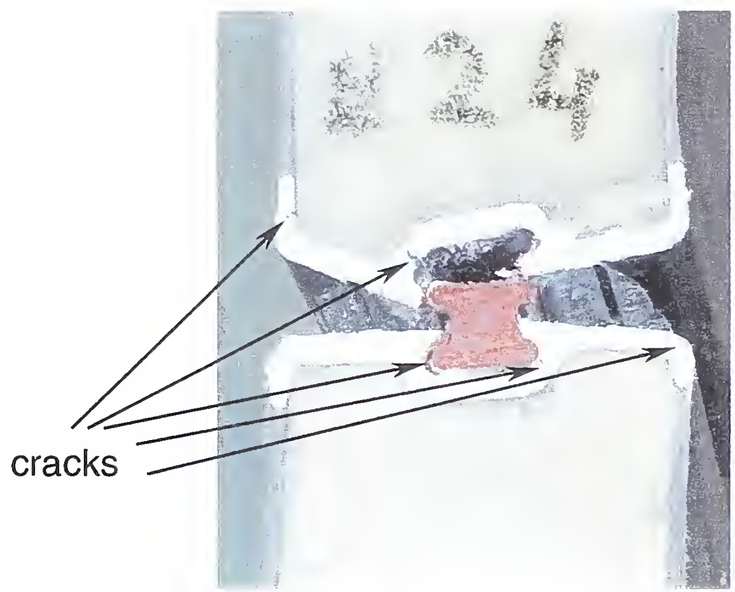


Fig. 5 "Double" tensile test with foam infill, toggle and adhesive

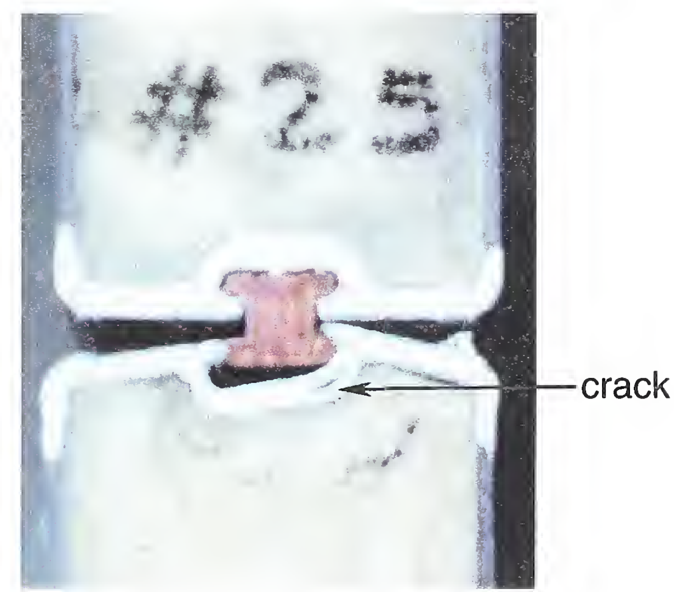
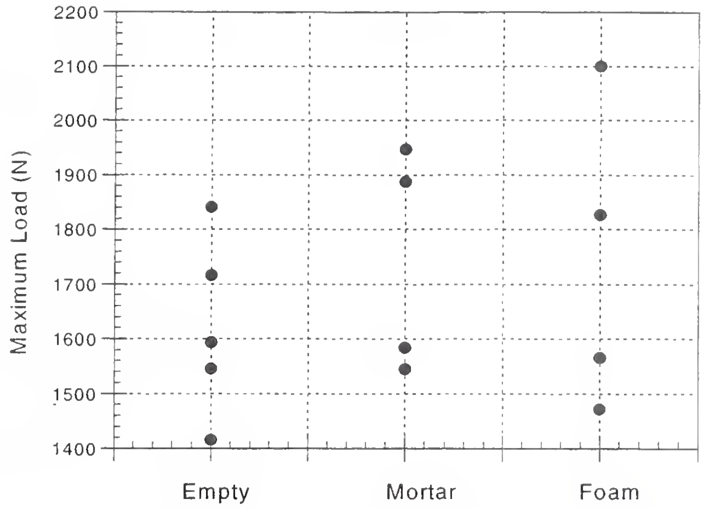


Fig. 6 "Double" tensile test with foam infill, toggle and no adhesive



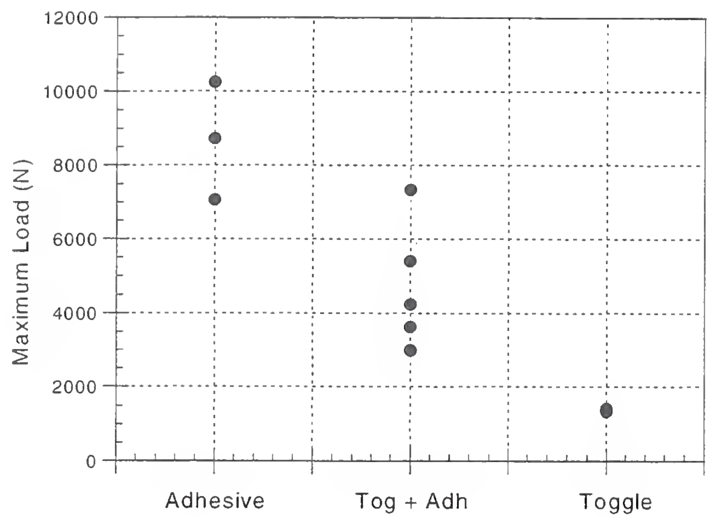
Summary statistics for maximum load for different infill material

Group	Count	Mean (N)	StdDev (N)	StdErr (N)
Air or empty	5	1622	163	73
Foam	4	1741	283	141
Mortar	4	1741	206	103

ANOVA Table for effect of insert material on maximum load

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	3.73663e7	3.73663e7	791.21	$\leq$ 0.0001
Infill	2	43279.9	21639.9	0.45821	0.6451
Error	10	472267	47226.7		
Total	12	515547			

Fig. 7 Effect of infills on joint strength



Summary statistics for maximum load for different joint conditions

Group	Count	Mean (N)	Std.Dev (N)	StdErr (N)
Adhesive	3	8682	1587	916
Tog+Adh	5	4721	1717	768
Toggle	3	1387	40	23

ANOVA table for effect of type of joint

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	2.63278e8	2.63278e8	125.13	≤0.0001
Joint	2	8.00938e7	4.00469e7	19.034	0.0009
Error	8	1.68321e7	2.10402e6		
Total	10	9.69259e7			

Ad-hoc test of differences of group means

	Difference (N)	Std. Err. (N)	Prob
Tog+Adh - Adhesive	-3961	1059	0.0175402
Toggle - Adhesive	-7295	1184	0.000919625
Toggle - Tog+Adh	-3334	1059	0.0398543

Fig. 8 Effect of interlocking, bonding, or both on joint strength

Fig. 9m Test 16 (single, mortar infill, toggle, no bond)

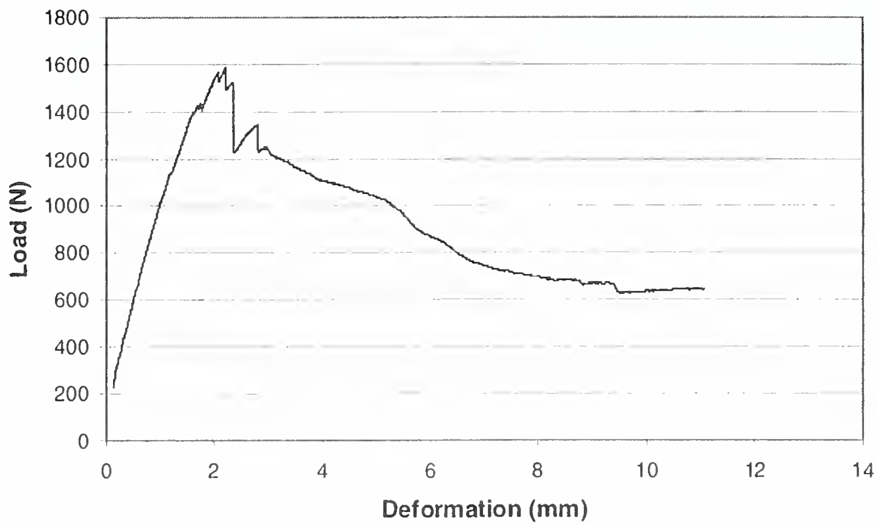


Fig. 10m Test 25 (double, foam infill, toggle, no bond)

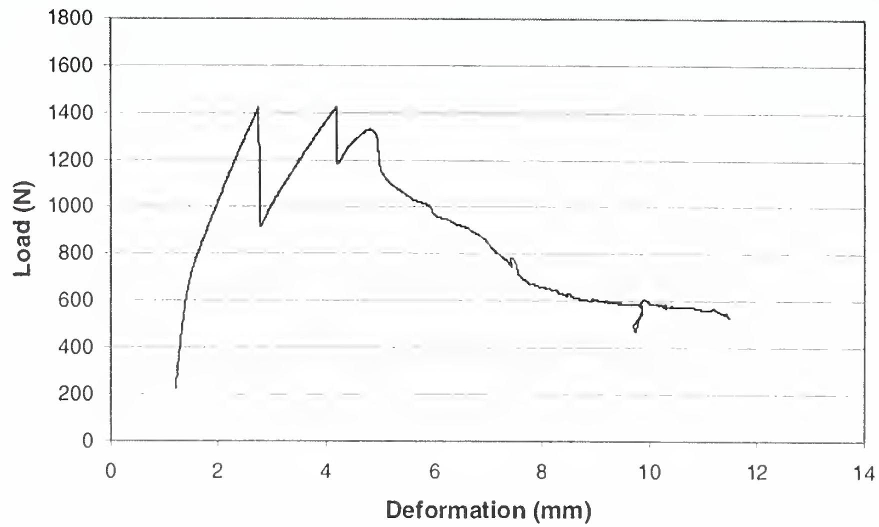


Fig. 11m Test 30 (double, bond only)

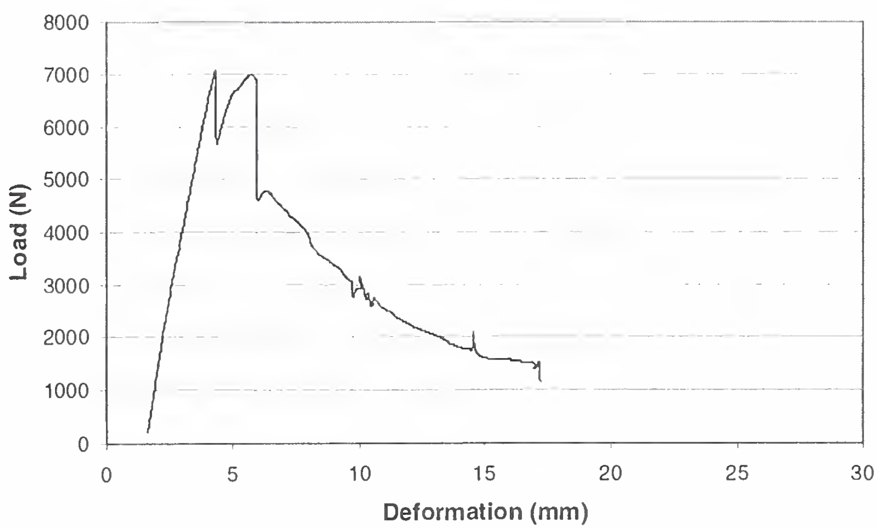


Fig. 12m Test 32 (double, toggle and bond)

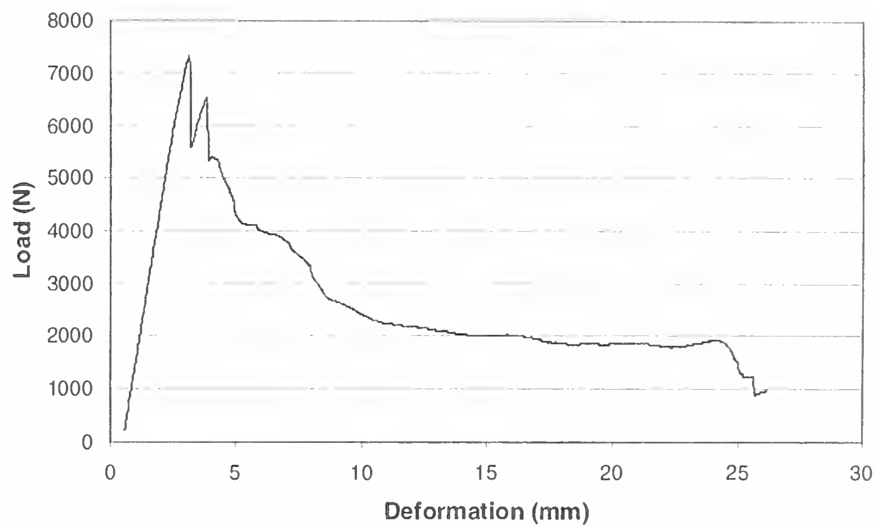


Fig. 9 Test 16 (single, mortar infill, toggle, no bond)

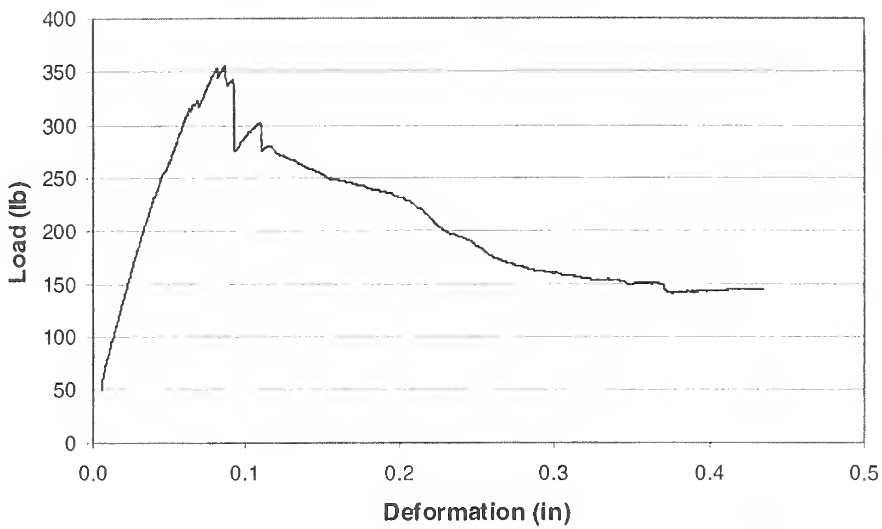


Fig. 10 Test 25 (double, foam infill, toggle, no bond)

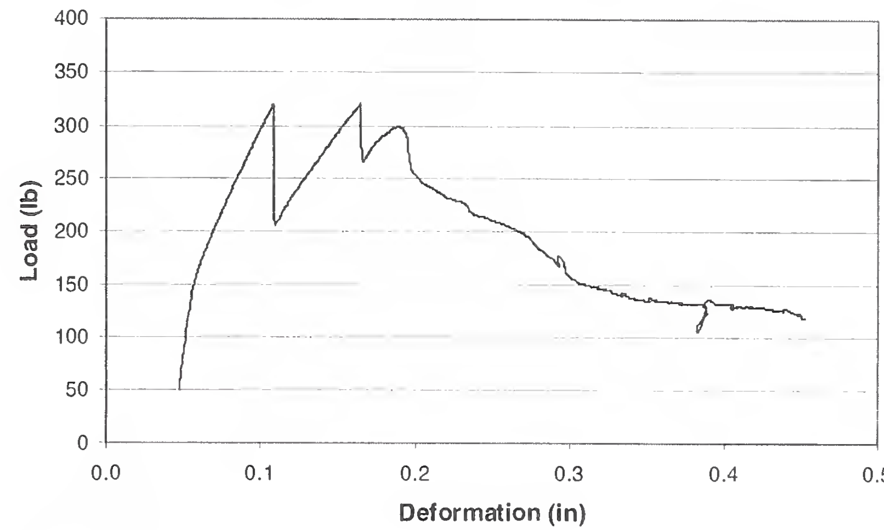


Fig. 11 Test 30 (double, bond only)

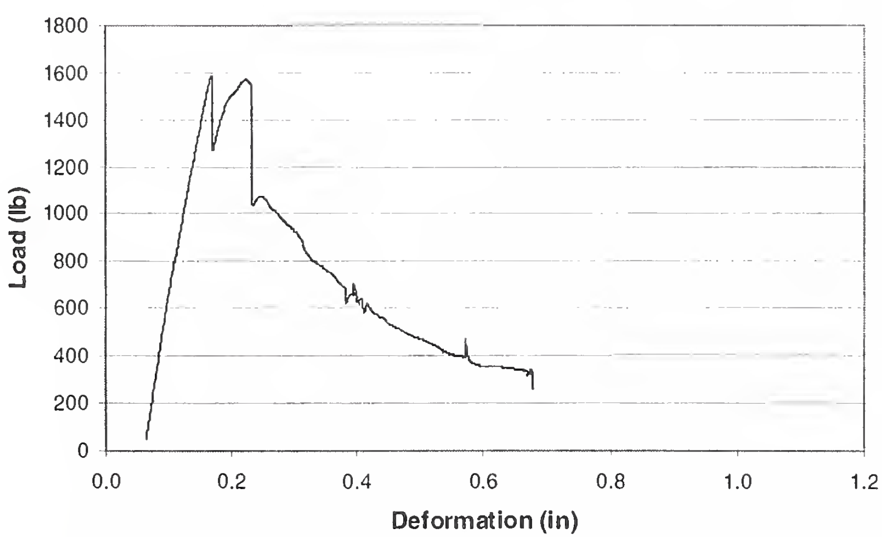


Fig. 12 Test 32 (double, toggle and bond)