On Testing the Failure Criterion of Bonding Agents for Use as Plate Structural Bonding for the Strengthening of Concrete Structures

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Abstract

The paper describes laboratory tests carried out in order to evaluate a test method prEN 12188 on *»Determination of Adhesion Steel-to-steel for Characterisation of Structural Bonding Agents«*, prepared by CEN TC104 SC8 WG3 on Structural Bonding.

The paper briefly introduces the strengthening of concrete structures by the method of structural bonding, gives an introduction to a failure criterion applicable to bonding agents and comments on the test method prEN 12188.

Several bonding agents were used for various test-series. However, this paper only reports on selected test series including NOR 385 (formerly IR 3310) from *Norco,* Sikadur 30 and Sikadur 31 from *Sika*. The test results found and observations made are presented, and it is concluded that the test method prEN 12188: *»Determination of Adhesion Steel-to-steel for Characterisation of Structural Bonding Agents«*, is suitable for the determination of the strength parameters of the tested bonding agents in an ordinary testing laboratory for building materials.

Keywords. Bonding agent, failure criterion, failure modes, steel plate bonding, strengthening of concrete structures, test method, testing.

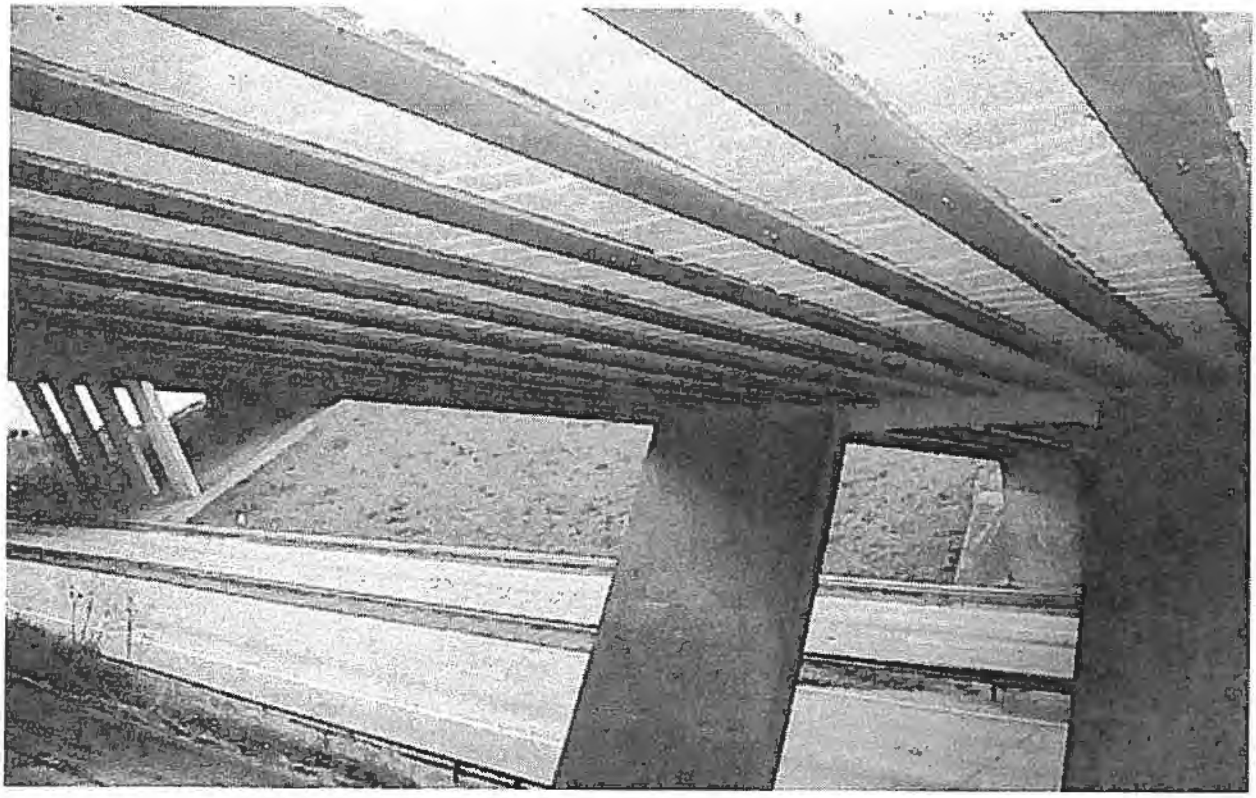


***Figure 1**. The soffit of a motorway bridge, strengthened by epoxy bonded steel plates. In this case the concrete slab needed strengthening due to lack of reinforcement. Bonded steel- to-steel as well as steel-to-concrete connections are used.*

Introduction

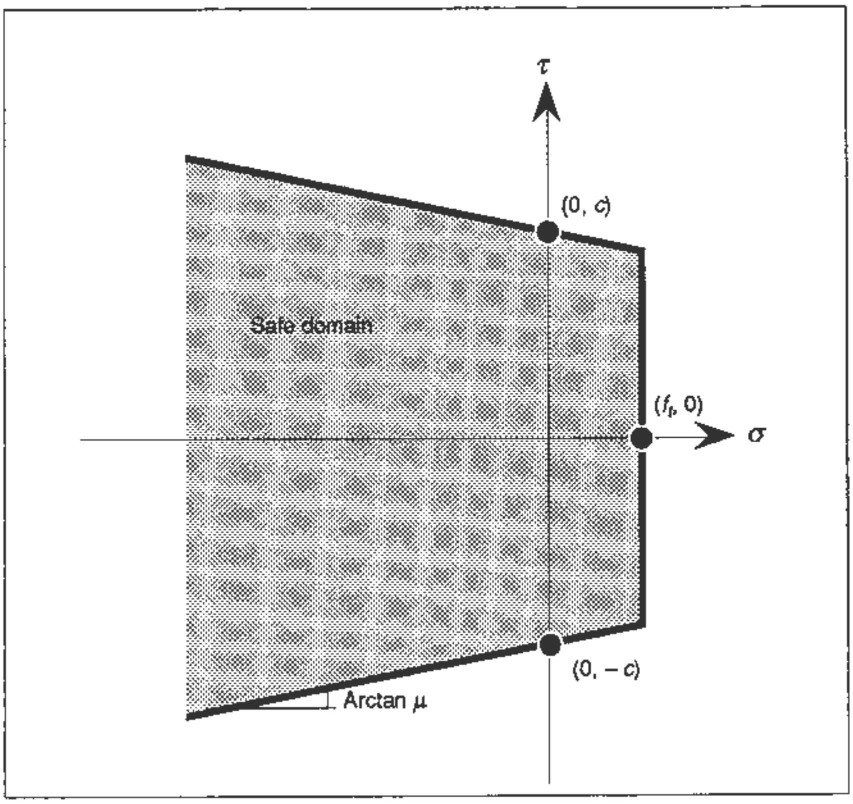
Background

Today, polymer-based bonding agents, e.g. epoxy, are used for steel plate bonding and Carbon Fiber Reinforced Polymer laminates for the purpose of strengthening concrete structures, brick walls, cast iron and steel structures. The method of strengthening concrete structures by epoxy bonded steel plate was first introduced by *R. l'Hermite* [1967, 1967] and continued by *J. Bresson* [1971, 1972]. Today, the method is applied worldwide and has been a great success when upgrading the load bearing capacity of bridges of reinforced concrete.

There are various reasons for carrying out a strengthening of a reinforced concrete structure. The main reasons are an increase of load, incorrect structural design (i.e. unsatisfactory safety against failure, unacceptable crack width or deflection) or degradation of the concrete structure due to either corrosion of rebars or disintegration of concrete. However, the method of strengthening concrete structures by steel plate bonding and CFRP laminates has its limitation – the concrete should be intact and have a strength sufficient for carrying the stresses from the external reinforcement (i.e. the bonded steel plates) to the internal reinforcement of the structure. High intensity of cracks (e.g. delamination) is the main reason why strengthening by steel plate bonding is sometimes refused. When possible the method is an excellent, convenient and cheep method of renovation.

The method of structural bonding as a principle of the strengthening of concrete structures has now become a part of common repair work in many countries. The design of structural bonding follows the general principles of structural design, e.g. given in the European Code EC 2, but there is a need for standard test methods for the inspection and control of construction work.

Figure 2. Typical failure envelope for a material under a stress field of normal stress σ and shear stress τ. The shaded open space of the diagram contains combinations of normal stress σ and shear stress τ which will not lead to failure of the material. The safe domain is bounded by the failure envelope (failure criterion).



The Working Group WG3 on »Structural Bonding«, *Comité Européen de Normalisation,* CEN TC104 SC8 has prepared a test method, prEN 12188 on *»Determination of Adhesion Steel-to-steel for Characterisation of Structural Bonding Agents«*. The test procedure has been tested at the *Technical University of Denmark* in cooperation with the *AEClaboratory* in order to evaluate the test method proposed.

As an introduction to the tests carried out the theoretical background of the test method is presented. Furthermore, some comments are made on the inspection of structural bonding.

Four students took an active share in the testing: *Bo Christensen, Christian Frandsen, Saeed Rahmani* and *Jeppe Schmidt*. The tests were carried out during 1994.

Failure Criterion for Brittle Materials

When failure occurs in brittle materials it is observed that the failure takes place along a plane section. When two bodies are bonded together with a bonding agent the failure criterion of the body shall be applied if the failure plane is situated in the body, while the failure criterion of the bonding agent shall be applied when the failure plane is situated in the joint.

Failure will occur when the normal stress σ and the shear stress τ reach values which obey the failure criterion, i.e. $f(\sigma, \tau) = 0$, in the most critical section of the material.

The failure criterion of a material like a bonding agent could be very complicated, but for the purpose of designing the strengthening of concrete structures by plate bonding applying partial safety factors, cf. EC 2, a simple approximation is valid. The simplest way of describing a failure criterion is given in Figure 2. Here the failure criterion is given by three straight lines, i.e. by the following three strength parameters which are material constants:

- The coefficient of friction μ, i.e. the numerical value of the slope of the inclined lines.
- The cohesion c, i.e. the shear capacity when $\sigma = 0$.
- The resistance against separation f_t, i.e. the pure tensile strength.

This simple failure criterion may worded as follows: »When the numerical value of the shear stress τ is

$$|\tau| = c - \mu\sigma$$

a *sliding failure* will occur. When the greatest value of the tensile stress σ is

$$\sigma = f_t$$

a *separation failure* will occur«.

As seen from Figure 2 the simple failure criterion given above determines an open domain bound by three straight lines. The domain containing the origin (0, 0) corresponds to stress fields not leading to failure.

Tests have shown that this simple failure criterion is valid in practice for many building materials like concrete, mortar, steel and several types of bonding agents.

Strengthening by Steel Plate Bonding

The failure criterion given above may be applied in order to determine the safety against failure of a bonded construction joint in a given structure, loaded mechanically. By the usual structural analysis the internal forces of the structure are calculated, i.e. the normal and shear forces, and the bending and twisting moments.

Generally, it is required that failure of construction joints, i.e. the bonding agent, does not occur before the failure takes place in the surrounding building material, i.e. the concrete.

Thus, this requirement yields that the stress field of the construction joint shall be found in the safe domain of the (σ, τ)-diagram, cf. Figure 2.

Partial Safety Factors

In order to obtain a sufficient safety against failure, the safety method of the Eurocode EC 2 is applied. Briefly explained, the loads of the structure are multiplied by loads factors (> 1) and the strength parameters are divided by materials factors (> 1). The structural analysis is carried out applying these design values. The safety against failure is accepted if the following can be shown:

- No occurence of failure of any construction joint (i.e. the bonding agent) of the structure.
- If the load of the structure increases to such a level that failure occurs in the structural material, no failure of any construction joint (i.e. the bonding agent) takes place.

Testing and Inspection

The design method for structural bonding described above requires the following documentation concerning the bonding agents and the near-to-surface layers of the concrete:

- The characteristic values of the strength parameters of the bonding agents shall be known and presented as characteristic values according to EC 2 in the data sheet for each of the bonding agents on the market.
- It shall be documented by identification tests that the bonding agents have characteristic strength parameters fulfilling the requirements.

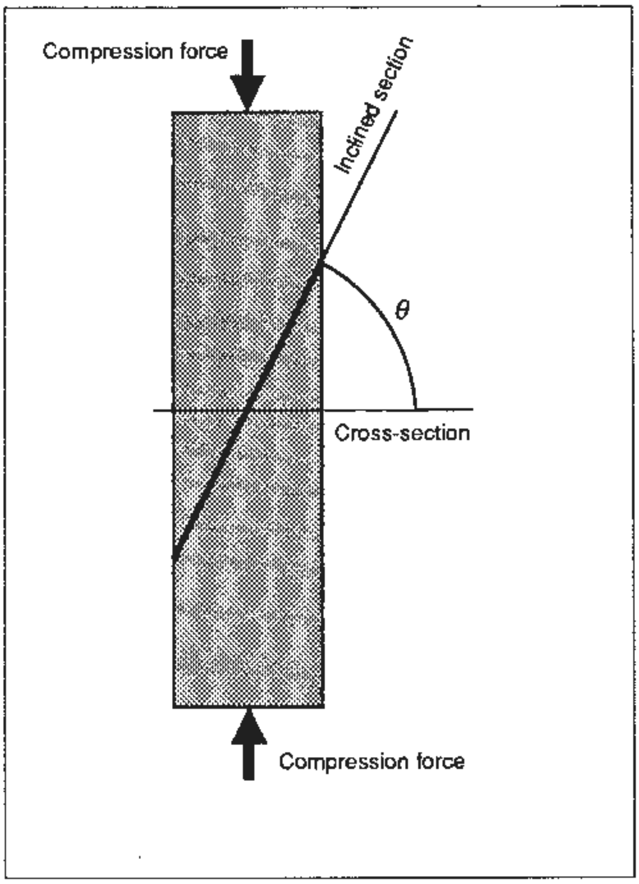


Figure 3. A scarf-jointed test prism in compression. θ denotes the angle from the cross-section of the test prism to the inclined section.

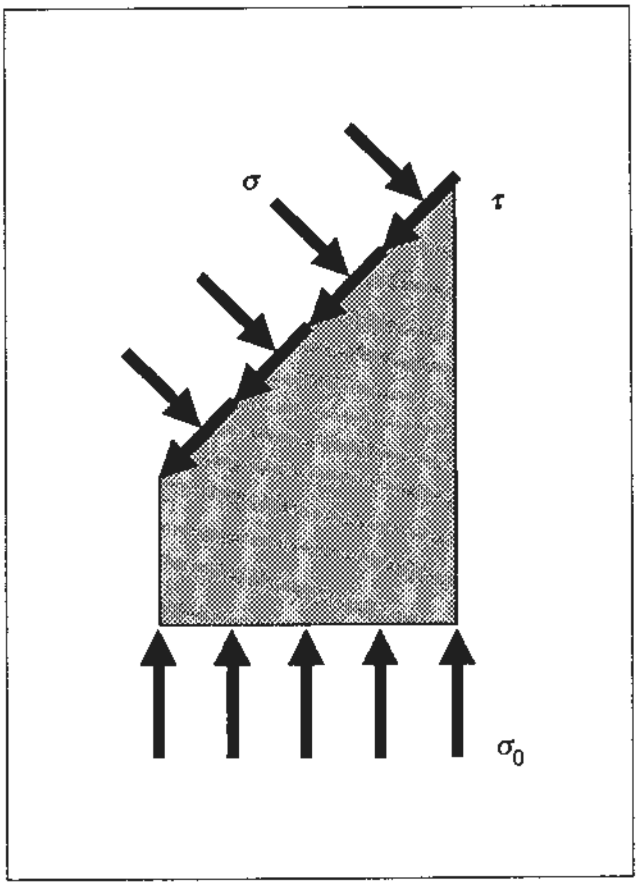


Figure 4. The stresses of the inclined section are normal stresses σ and shear stresses τ. The notation of the slant shear stress is σ_0.

- It shall be documented by pre-testing or full-scale trial testing on the work site that the bonding agents fulfil the requirements under practical conditions.
- It shall be documented by testing of control parameters within decent inspection sections that the strength parameters are under control during the whole construction period.

The Need for Test Methods

By inspection and testing it shall be documented that concrete, bonding agent and the bonded joints of a structure have achieved the assumed strength parameters. Here, the near-to-surface layer of the concrete plays an important role. Chipping hammer, pneumatic scabbler, rotary miller and flame cleaner will introduce defects (microcracks) in the concrete surface. Hence, it shall be cleaned by e.g. sand blasting or hydro removal. The inspection and testing usually cover:

- *Thin section analysis* of the sand blasted concrete surface in order to inspect for defects.
- *Slant shear test and pull-off test* of jointed steel-to-steel semi prisms and steel-to-steel dollies respectively in order to inspect the quality of the bonding agents applied.
- *Pull-off testing* of the steel-concrete and steel-steel connections in order to inspect the human factor in-situ.
- *Impact echo testing* of the bonded steel plates and the CFRP laminates in order to inspect the applied bonding agants for entrapped air voids.

The slant shear test applied shall be able to determine the following strength parameters:

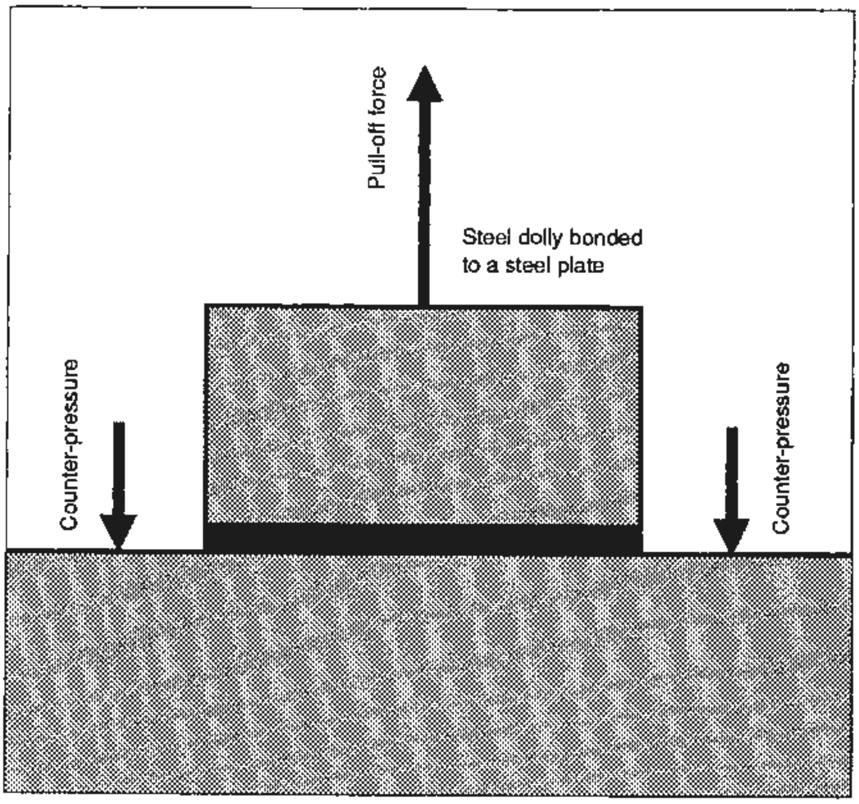


***Figure** 5. A circular steel dolly is bonded with a bonding agent to a steel plate. When the bonding agent has hardened the dolly is tested by a pull-off test in pure tension until failure. The pull-off strength f_t represents the resistance against separation (tensile strength of the bonding agent) and the failure mode is a separation failure.*

- The coefficient of friction μ, i.e. the numerical value of the slope of the inclined lines.
- The cohesion c, i.e. the shear capacity when $\sigma = 0$.
- The resistance against separation f_t, i.e. the pure tensile strength.

The test method, prEN 12188: *»Determination of Adhesion Steel-to-steel for Characterisation of Structural Bonding Agents«* will satisfy the requirements presented:

- By *the pull-off test* it is possible to determine the resistance against separation f_t, i.e. the pure tensile strength of the bonding agent, cf. Figure 5.
- By *the slant shear test* it is possible to determine the coefficient of friction μ and the cohesion c of the bonding agent, cf. Figure 3.

Several tests have to be performed in order to achieve the characteristic values of the strength parameters. Furthermore, the failure during testing must occur in the bonding agent in order to determine the strength parameter of the bonding agent.

This requires that the surrounding material is stronger than the adherence material in the joint. Thus, it may be necessary to apply high strength materials, e.g. granite or steel as a test specimen. WG 3 has chosen steel.

Description of the Test Method

By means of testing scarf-jointed steel prisms bonded with a bonding agent and steel dollies bonded to a steel plate the failure criterion of the bonding agent was determined, observing that the failures occur mainly within the bonding agent.

Sliding Failure

The test prisms applied for the slant shear test had inclined bonded joints, θ equal to 50°, 55°, 60°, 65° and 70°. They were tested in compression until failure, cf. Figure 3, and strength and the failure mode were observed. The corresponding values of the stresses σ and τ were plotted in a (σ, τ)-coordinate system, cf. Figure 2, and fitted by applying linear regression analysis technique. From this procedure the coefficient of friction μ and the cohesion c were determined.

Separation Failure

The dollies were tested in tension by pull-off test until failure, cf. Figure 5. The pull-off strength represents the resistance against separation f_t.

Preparation of Test Specimens for Slant Shear Test

Test Specimens

The test specimens were prismatic steel specimens with a square cross section of 40 mm by 40 mm and a length of 160 mm. Each of the test prisms were cut into two identical parts (semi-prisms) by a saw at an angle θ to the cross section of the prism, cf. Figure 6 and 7. The sawn surfaces were grit blasted and cleaned, applying acetone.

Preparation

Sets of two identical semi-prisms were bonded with the bonding agent in such a way that when hardening took place the bonded joints had horizontal positions. The bonded semi-prisms rested on tracks during the period of hardening in order to become right true prisms.

The steel-to-steel bonding was carried out in accordance with the specification given by the suppliers. After hardening the excess bonding agent was cut away. For each test prism the thickness of the bonding joint was determined by means of an optical crack width gauge. The joint thickness was determined as the average of the joint thicknesses measured at the mid points of the four sides of the prism. A joint thickness of 2 mm was aimed at.

Preparation of Test Specimens for Pull-off Test

The test specimens were bonded steel dollies (Ø 50 mm) bolted to steel rods for tension tests, cf. figure 8, in order to ensure axial loading. The test method EN 1542: »Pull-off Test« was applied.

Test Procedure

Number of Tests

For each set of test conditions, two scarf-jointed prisms (for each angle θ) were tested (prEN 12188 recommends three specimens).

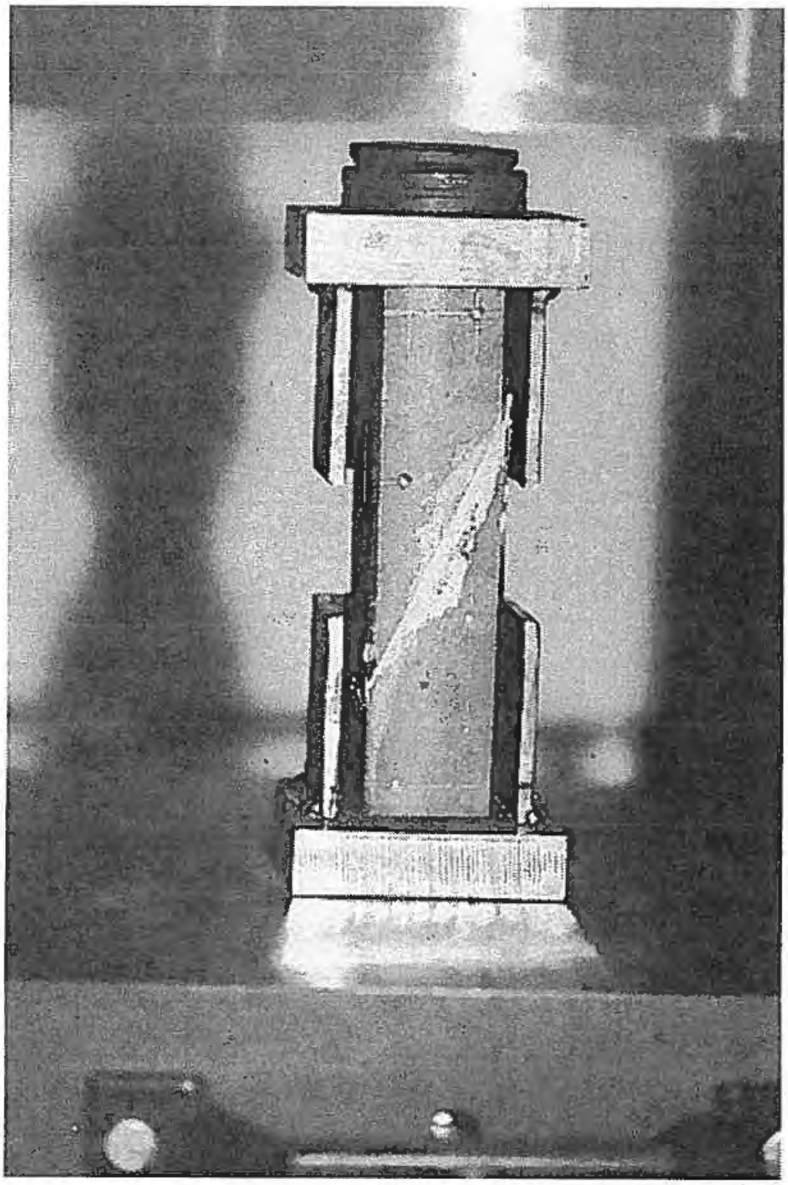
Temperature

The test prisms were maintained at the temperature condition specified for not less than 16 hours before testing commences. Testing was carried out at 20 °C. The proposal specifies a temperature of 21 ± 2 °C unless any other temperature condition is declared by the client.

Loading Procedure

The loading procedure was in accordance with the specification for the testing machine. The scarf-jointed prisms were loaded according to the standard procedures for testing cylinders for compressive strength at a stress rate of 0.8 MPa/s (prEN 12188 requires between 0.5 and 1.0 MPa/s).

Figure 6. A steel prism test specimen for slant shear test placed in a testing machine. Note the steel sheet protection device at the bottom platen placed in order to protect the sharp-edged semi-prism from being damaged when the sliding failure occurs, cf. figure 7. A glass protection plate is placed in front of the testing machine in order to make observation close to the specimen possible.



Failure modes

The failure modes achieved were described, classified and reported. An failure mode was accepted if the failure plane passed entirely through the adhesion agent. The observation of a scarf-jointed prism or a dolly was rejected if the failure occurred at the interface between the steel surface and the bonding agent, or if more than 10 per cent of the failure plane was taking place at the interface.

Calculation of the slant shear strength

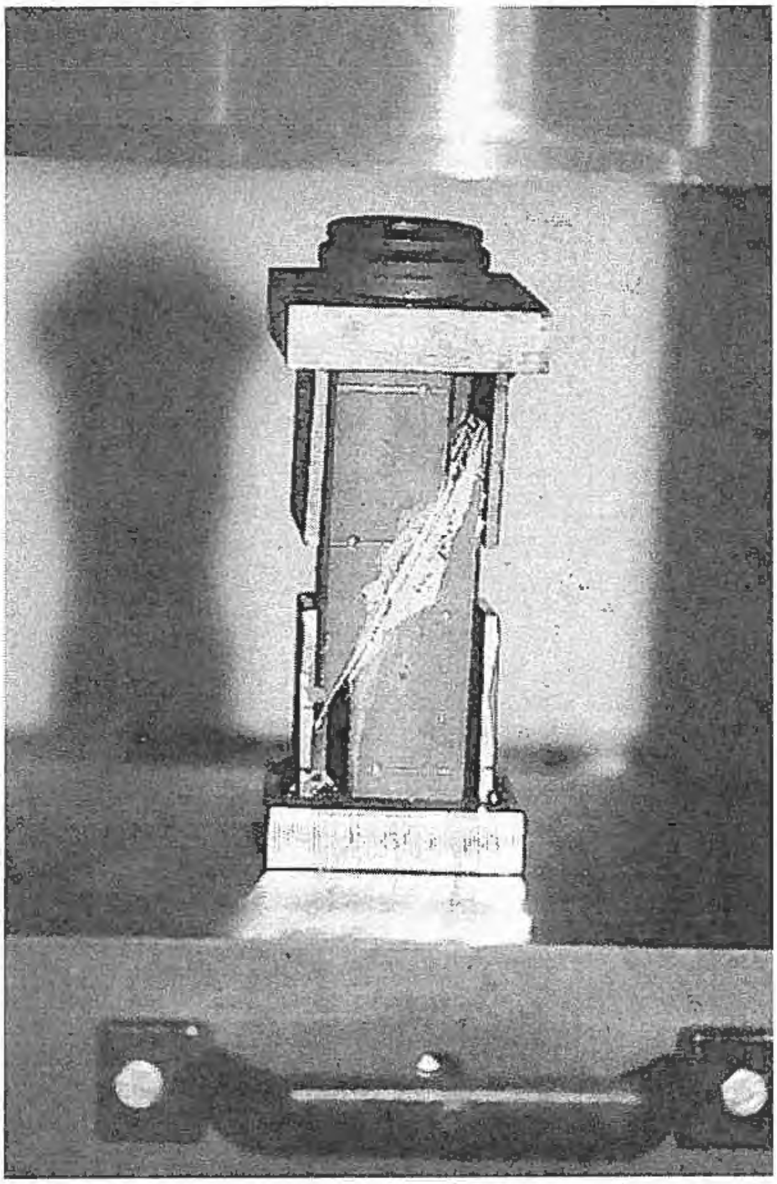
The slant shear strength was calculated for each specimen by dividing the load at failure by the cross-sectional area.

The stresses σ and τ with respect to an angle θ between the cross-section and the joint were calculated by means of the following formulae, derived from Figure 4:

$$\sigma = \sigma_0 \cos^2\theta$$
$$|\tau| = \sigma_0 \cos\theta \sin\theta$$

The coefficient of friction μ and the cohesion c, is found by regression analysis from (σ, τ

Figure 7. A steel prism slant shear specimen after the sliding failure has taken place. The failure takes place suddenly and it is a brittle failure, i.e. the deformation before failure is small.



The Tests Performed

Bonding Agents Applied

Four bonding agents were used for the tests, Concretin SK 41 from *Hilti*, NOR 385 from *Norco*, and Sikadur 30 and Sikadur 31 from *Sika*. These bonding agents were solvent-free thixotropic epoxy products and were supplied as a base material (A) and a hardener (B).

Numbers of Tests Specimens

Four series of tests were carried out (i.e. one of each with Concretin SK 41, Sikadur 30, Sikadur 31, and NOR 385 as bonding agent), with various conditions:

- At least two sets of five specimens each (identical prisms) for slant shear tests in compression, having the following angles of joint sections: $\theta = 50°, 55°, 60°, 65°$ and $70°$.
- At least two sets of one specimen (identical prisms) for slant shear tests in tension, having the following angles of joint sections: $\theta = 30°$ and $70°$.
- Two sets of one specimen (identical dollies) for pull-off tests ($\theta = 0°$).

The following periods of hardening were used:

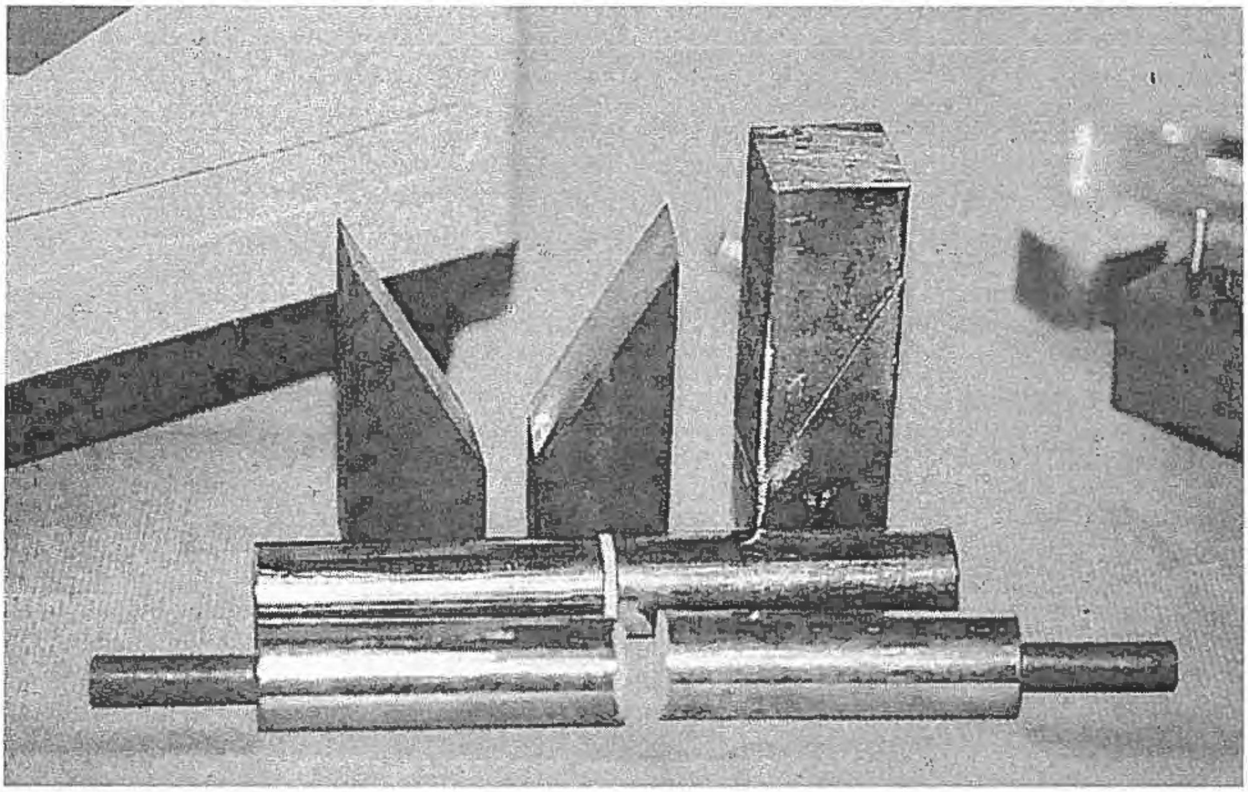


***Figure 8**. Steel prisms for slant shear test and steel dollies for pull-off test. The scarf jointed steel prisms have a 40 ×40 mm cross-section and a length of 160 mm. The dollies shall have a diameter of at least 50 mm, and a length of at least 50 per cent of the diameter. The dollies are bolted to appx. 1 m long steel rods in order to ensure centric loading by tension in the testing machine.*

- *Sikadur 30*. Two series with periods of 5 and 26 days respectively of hardening at 20 °C, cf. Table 4 and Figure 13 for the slant shear tests in compression and tension as well as for the pull-off tests.
- *Sikadur 31*. One series with a period of 7 days of hardening at 20 °C, cf. Table 1 for the slant shear tests in compression, and Figure 9.
- *NOR 385*. Three series with periods of 4.5, 7 and 10 days respectively of hardening at 20 °C, cf. Table 2 for the slant shear tests, Table 3 for the pull-off tests, and Figures 10, 11 and 12.

Test Data Achieved

After the hardening period the excess bonding agent was removed and the width of the joint was measured by an optical gauge.

Slant Shear Test in Compression and Tension

Some of the bonded steel prisms were placed and tested in compression, cf. Figure 6, others were tested in tension. In order to make it possible to observe the sliding failure closely a container of perspex was placed around the specimen. The compression was applied at a rate of appx. 0.8 MPa/s. The tension was applied at a rate of appx. 0.4 MPa/s. The ultimate load capacity was recorded, and the section of failure was studied in order to observe any defect.

***Table 1**. Resistance to sliding failure determined for the bonding agent Sikadur 31 by slant shear test. σ_0 denotes the slant shear strength and the set (σ, τ) denotes a point of the failure criterion of the bonding agent. Due to lack of cleaning some test specimens failed partly at the interface between steel and bonding agent. In the cases marked ■ more than 10 per cent of the sliding area took place at the interface. The introduction of a cleaning process using acetone solved this phenomenon.*

θ Degree		σ_0 MPa	σ MPa	τ MPa
50°	■	48.31	19.96	23.79
50°	■	40.04	16.54	19.71
55°	■	40.28	13.25	18.93
55°	■	41.94	13.80	19.70
60°		41.32	10.33	17.89
60°	■	36.05	9.01	15.61
65°		33.91	6.06	12.99
65°	■	35.07	6.26	13.43
70°		38.26	4.48	12.30
70°		37.52	4.39	12.06
Curing at 20 °C		6 days of hardening		

Pull-off Test

The bonded steel dollies were bolted to steel rods and placed and tested in tension, cf. Figure 8. The tension was applied at a rate of appx. 0.4 MPa/s. The ultimate load capacity was recorded and the section of failure was studied in order to observe any defect.

Cleaning the Specimens before Bonding

After testing to failure the specimens were placed in a heating cupboard about 24 hours at a temperature of appx. 250 °C. Then the specimens were sandblasted and cleaned by acetone, ready for a new bonding and testing.

Interpretation of Observations

The intension of the tests carried out was not to study the bonding agents but to evaluate the proposed test method prEN 12188. However, the shear stresses τ versus the normal stresses σ when failure occurred are plotted in Figures 9-13 and represents the failure criterion achieved. The strength parameters found by linear regression analyses are shown in Table 5.

θ Degree	σ_0 MPa	σ MPa	τ MPa	σ_0 MPa	σ MPa	τ MPa	σ_0 MPa	σ MPa	τ MPa
50°	35.44	14.64	17.45	30.59	12.64	15.07	40.10	16.57	19.74
50°	39.91	16.49	19.65	26.43	10.92	13.01	37.16	15.35	18.30
55°	35.56	11.70	16.71	31.27	10.29	14.69	36.05	11.86	16.94
55°	33.05	11.87	15.53	35.25	11.60	16.56	35.25	11.60	16.56
60°	33.91	8.48	14.68	30.41	7.60	13.17	32.92	8.23	14.26
60°	33.54	8.38	14.52	29.92	7.48	12.96	32.92	8.23	14.26
65°	26.88	5.16	11.06	28.08	5.02	10.76	39.12	6.99	14.98
65°	28.63	5.11	10.97	29.31	5.23	11.23	34.76	6.21	13.32
70°	30.78	3.60	9.89	43.47	5.09	13.97	43.84	5.13	14.09
70°	32.92	3.85	10.58	38.69	4.53	12.43	42.18	4.93	13.56
Curing at 20 °C	4.5 days of hardening			7 days of hardening			10 days of hardening		

***Table 2**. Resistance to sliding failure determined for the bonding agent NOR 385 by slant shear test at various periods of hardening. σ_0 denotes the slant shear strength and the set (σ_0, τ) denotes a point of the failure criterion of the bonding agent at the hardening periods indicated. θ denotes the angle from the cross-section of the test prism to the inclined joint, cf. Figure 3.*

***Table 3**. The resistance to separation f_t determined for the bonding agents Sikadur 31 and NOR 385 by pull-off test. Only minor defects were observed at the section of failures.*

Pull-off strength	f_t	f_t	f_t
Dolly No. 1, MPa	10.24	15.09	13.39
Dolly No. 2, MPa	10.04	14.59	13.39
Average, MPa	10.14	14.84	13.39
Bonding agent	NOR 385	NOR 385	NOR 385
Hardening period	4.5 days	7 days	10 days

Discussion and Conclusion

Generally speaking test method prEN 12188 on *»Determination of Adhesion Steel-to-steel for Characterisation of Structural Bonding Agents«* was found suitable. However, a few corrections and additions could be of interest for the user:

- A stress rate of 0.4 MPa/s in tension was found suitable for the pull-out test and a stress rate between 0.2 and 0.5 MPa/s should be recommended.
- A device for the protection of the top semi-prism in the slant shear test should be recommended in order to avoid damaging the sharp edge.
- A glass plate is recommended to protect the observer from a brittle failure of the scarf-jointed steel prism.

Appendix

Definitions

For the purpose of the test method the following terms and characteristics have been applied:

Compressive Stress

The compressive stress σ_0 of the test prism is the compressive force F carried by the test prism per unit area A_c of the cross-section of the prism, that is

$$\sigma_0 = \frac{F}{A_c}$$

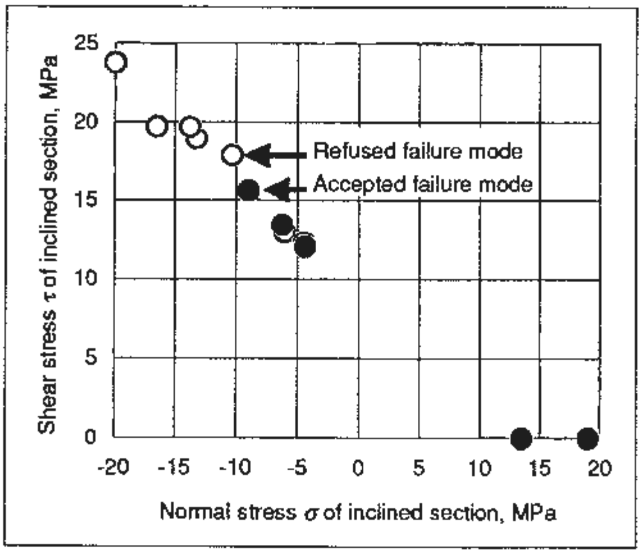


***Figure 9**. Diagram for shear stresses τ versus normal stresses σ when failure occurs. The joints were bonded with Sikadur 31 and the hardening period was 6 days at 20 ℃.*

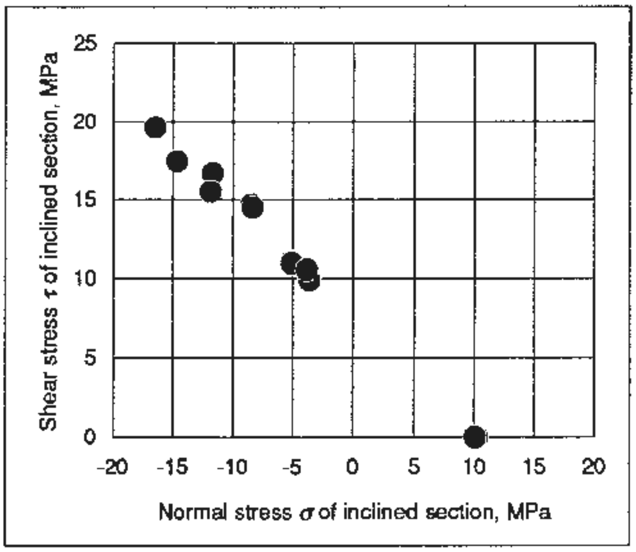


***Figure 10**. Diagram for shear stresses τ versus normal stresses σ when failure occurs. The joints were bonded with NOR 385 and the hardening period was 4.5 days at 20 ℃.*

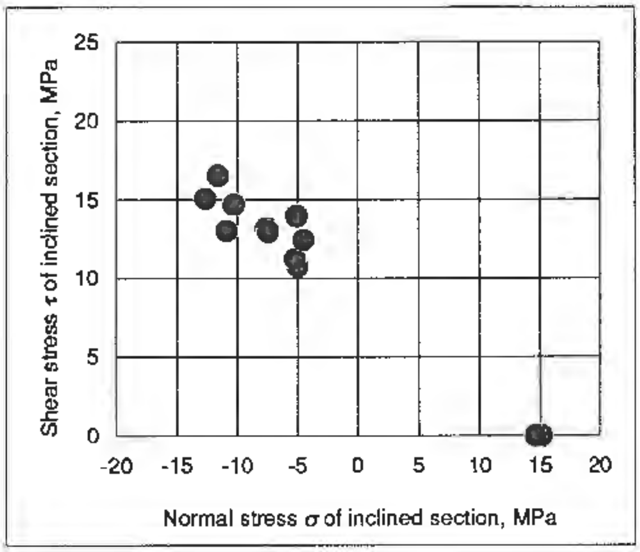


Figure 11. Diagram for shear stresses τ versus normal stresses σ when failure occurs. The joints were bonded with NOR 385 and the hardening period was 7 days at 20 ℃.

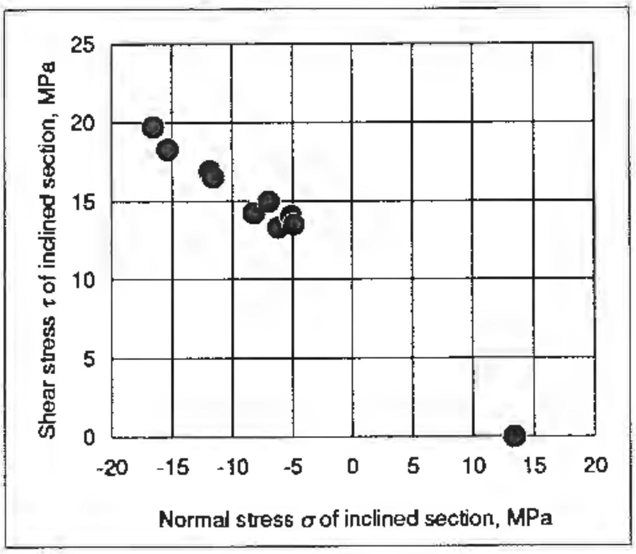


Figure 12. Diagram for shear stresses τ versus normal stresses σ when failure occurs. The joints were bonded with NOR 385 and the hardening period was 10 days at 20 ℃.

Stresses of an Inclined Section

The stresses of an inclined section of the test prism will be a normal stress, σ, and a shear stress, τ, cf. Figure 4,

$$\begin{aligned}\sigma &= \sigma_0 \cos^2\theta \\ |\tau| &= \sigma_0 \cos\theta \sin\theta\end{aligned}$$

Here θ denotes the angle from the cross-section of the test prism to the inclined section, cf. Figure 3.

Pull-off Strength

Maximum tensile stress carried by the bonded joint in a pull-off test as shown in Figures 5 and 8, and defined by the maximum tensile force F_u divided by the area of the bonded section A_c, i.e.

Separation Failure

A separation failure is a mode of failure where the failure occurs along a slipplane in such a way that the material on each side of the slipplane moves perpendicular to the slipplane, cf. Figure 8.

$$f_t = \frac{F_u}{A_c}$$

Sliding Failure

A sliding failure is a mode of failure where the failure occurs along a slipplane in such a way that the material on each side of the slipplane moves tangential with the slipplane, cf. Figure 7.

Slant Shear Strength

The compressive strength of a scarf-jointed test prism where failure occurs along the inclined bonded joint.

***Table 4**. Resistance to sliding failure and to separation failure for the bonding agent Sikadur 30 determined by slant shear test at various periods of hardening. The set (σ_0, τ) denotes a point of the failure criterion of the bonding agent at the hardening periods indicated. θ denotes the angle from the cross-section of the test prism to the inclined joint, cf. Figure 3. Compressive normal stress (compression) is indicated as a negative value while a tensile normal stress (tension) is indicated as positive.*

θ Degree	σ MPa	τ MPa	σ MPa	τ MPa
0°	21.5	0.0	27.1	0.0
0°	22.8	0.0	25.3	0.0
30°	12.9	7.4	24.0	13.9
30°	14.6	8.4	24.1	13.9
30°	–	–	21.3	12.3
70°	6.0	16.5	–12.0	32.9
70°	5.7	15.7	–9.8	26.9
70°	5.4	14.8	–11.3	30.9
50°	–27.9	33.2	–31.8	37.9
50°	–20.2	24.1	–23.0	27.4
50°	–25.9	30.8	–35.1	41.9
55°	–16.2	23.2	–22.7	32.4
55°	–19.3	27.6	–25.9	37.0
55°	–21.8	31.2	–28.8	41.1
60°	–16.7	29.0	–19.8	34.2
60°	–19.3	33.3	–18.2	37.1
60°	–17.2	29.8	–20.9	36.1
65°	–12.4	26.5	–16.1	34.5
65°	–13.6	29.2	–15.5	33.3
65°	–14.0	29.9	–15.5	33.3
Curing at 20 °C	5 days of hardening		26 days of hardening	

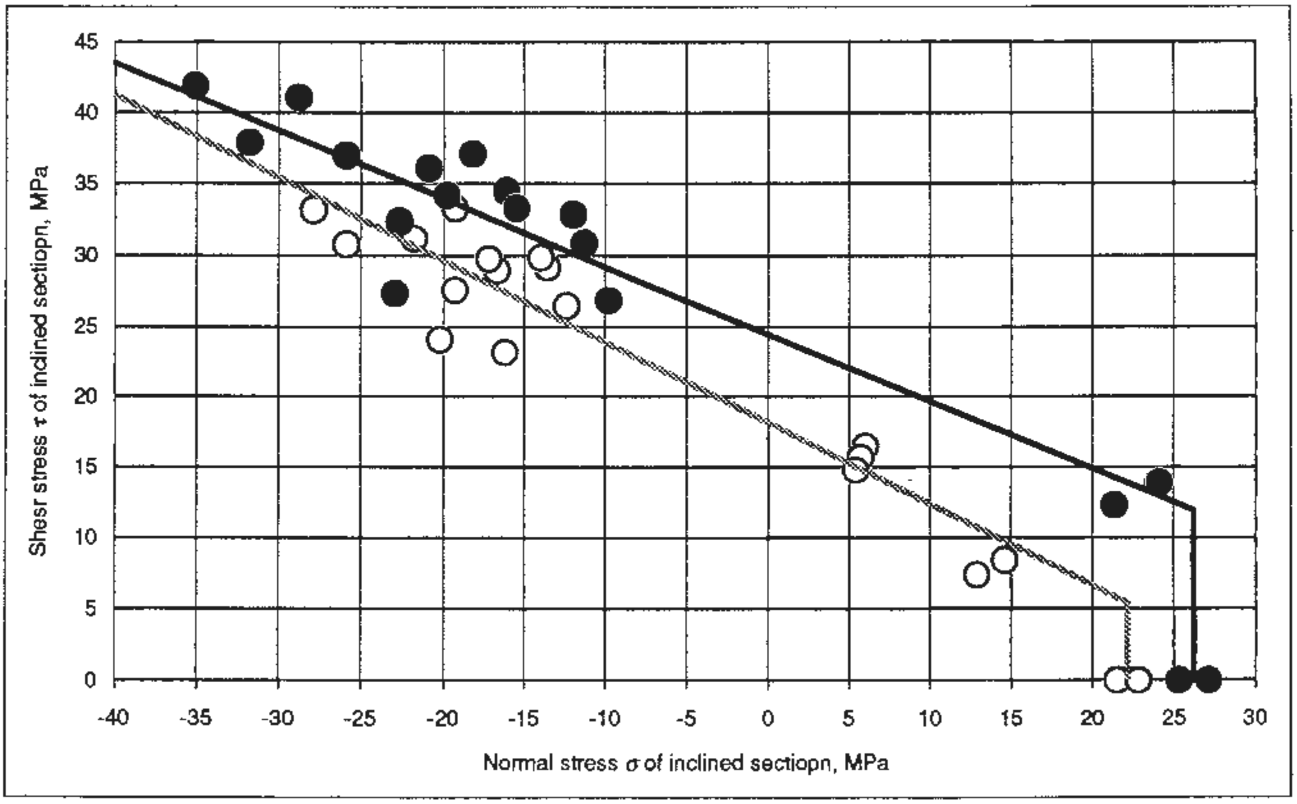


***Figure 13**. Diagram for shear stresses τ versus normal stresses σ when failure occurs. The test carried out is the the slant shear test, prEN 12188. The joints were bonded with Sikadur 30 and the hardening period was 5 days at 20 °C (○) and 26 days at 20 °C (●) respectively.*

***Table** 5. Strength parameters found by regression analysis of (σ, τ) observed by the test presented.*

Bonding agent	Hardening period	c, MPa	μ	f_t, MPa
NOR 385	4.5 days at 20 °C	7.7	0.73	10.1
NOR 385	7 days at 20 °C	9.9	0.43	14.8
NOR 385	10 days at 20 °C	10.8	0.51	13.4
Sikadur 30	5 days at 20 °C	18.0	0.58	22.2
Sikadur 30	26 days at 20 °C	24.7	0.47	26.2
Sikadur 31	7 days at 20 °C	7.6	0.60	10.0

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