Aluminum-zinc Alloy Coated Steel for Composite Slabs

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by

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SUMMARY

This paper presents experimental results of twenty pull-out tests involving four different metallic coatings and four different surface conditions. Results are also presented for six full-scale composite slab tests involving two different metallic coatings (AZ150 Galvalume and Z275 galvanized) on one composite steel deck profile. The shear-bond resistance between AZ150 Galvalume steel and concrete is greater than that of both ZF075 wiped coat galvanized and Z275 galvanized steel. Finally, the corrosion protection provided to the base steel by the metallic coatings exposed to concrete is discussed.

INTRODUCTION

Composite slab floor construction is used extensively in office and apartment buildings and has been well accepted over the past 30 years as a most efficient and economical light-weight floor system. Composite slab construction refers to a structural slab system created by compositely combining the structural properties of concrete and cold-formed steel decking. To develop the required composite action (mechanical interlocking resistance) between the concrete and steel deck, the steel deck must be able to resist horizontal shear and vertical separation between the concrete and steel deck. To achieve this, most common composite steel decks on the market today utilize a fixed pattern of embossments. For a more detailed discussion on composite slabs in general, see Reference 1.

Typically, composite steel decks have some type of surface coating for corrosion protection and vary in degree of application. The two most common coating applications on the market today are 1) ZF075 wiped coat galvanized, and 2) Z275 hot-dip galvanized. In Canada, wiped coat refers to a hot-dip, zinc-coated product that is wiped after the strip emerges from the zinc pot to produce a fully alloyed zinc-iron coating. The coating can also be produced by heat treating (galvannealing). Dofasco has recently introduced a new coating called Galvalume* which is being used on cold-formed steel building products such as siding and roof applica-

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*In Canada, Galvalume is a trademark of Dofasco Inc., Hamilton, Ontario.

tions, but not yet on composite steel decks. AZ150 Galvalume is an alloy coating nominally consisting of 55% aluminum, 43.4% zinc and 1.6% silicon by weight applied by the hot-dip process.

The purpose of this paper is to present composite slab test results of a comparison study between AZ150 Galvalume steel and Z275 hot-dip galvanized steel using one composite deck system (Lorlea's D-900C composite deck). This was done so that a proper comparison of the coating could be made, i.e., keeping certain parameters constant for all specimens and only varying the coating. Prior to testing the full-scale composite slabs, small-scale pull-out tests were carried out by Dofasco to establish the relative bond properties between the two and other coatings.

PULL-OUT TESTS

Pull-out tests were conducted to investigate the adhesion strength of various metallic coatings and surface conditions on smooth steel strips in contact with concrete. The three-digit number designates the total metallic coating mass on both sides of the steel sheet, expressed in g/m^2. Four materials were included in the program:

1) cold rolled (uncoated) steel
2) ZF075 wiped coat galvanized steel
3) Z275 regular spangle galvanized steel
4) AZ150 Galvalume steel

Each specimen was tested under two surface conditions, i.e., with slushing oil and cleaned with carbon tetrachloride. Two additional conditions were included for the Galvalume specimens, namely, with vanishing oil and with spray lacquer. The lacquer provided an additional protective layer to minimize any reaction of the Galvalume coating with the concrete. Two tests were made for each combination of variables, for a total of 20 pull-out tests.

Description of Test Specimens

Each steel specimen measured 50.8 mm × 406 mm (2 in. × 16 in.), had a nominal thickness of 1.52 mm (.060 in.), and a longitudinal V-bend of approximately 15° to ensure straightness.

Each specimen was cast in a concrete mould measuring 150 mm diameter by 300 mm high (6 in. × 12 in.) using normal density concrete, 2240 kg/m^3 (140 pcf) of 24 MPa (3500 psi) minimum compressive strength. Therefore, the embedded length of each specimen was 300 mm (12 in.). Each mould was vibrated after the concrete was poured and cured 31 to 34 days at room temperature.

Test Equipment and Instrumentation

An Instron tensile test machine was used in the pull-out test program. Anchor bolts and plates were used for mounting the test specimens in the machine.

Test Procedure

Each test specimen was anchored to the cross-head of the test frame and the grips were attached to the protruding steel specimen. The cross-head speed was 1.3 mm (0.05 in.) per minute until the point of first slip, after which the speed was increased to 5.1 mm (0.20 in.) until the ultimate load was achieved and then to 51 mm (2.0 in.) per minute. A graph of load versus cross-head travel was plotted for each specimen tested.

COMPOSITE SLAB TESTS

The laboratory test program was planned in an effort to simulate, as closely as practically possible, a typical composite slab installation found in building construction. Six full-scale composite slab specimens were tested, three with AZ150 Galvalume coating and three with Z275 galvanized coating. The steel decks were manufactured from the same nominal steel thickness of 0.914 mm (0.036 in.), having the same nominal embossment pattern and dimensions. Figure 1 shows a typical cross-section of the D-900C composite deck used (all figures appear at the end of the paper). Photographs of the general appearance of the AZ150 Galvalume and Z275 galvanized composite decks prior to testing are shown in Figures 2 and 3, respectively. Fabrication and testing of all composite slab specimens was based on References 2 and 3, whenever applicable.

Description of Test Specimens

All specimens had the same span length of 2400 mm (94.5 in), the same overall nominal slab depth of 140 mm (5.50 in.), the same nominal slab width of 900 mm (35.4 in.) and the same shear span of 600 mm (23.6 in.). The specimens were cast with the steel decks supported throughout using normal density concrete, 2350 kg/m^3 (145 pcf). Prior to placing of concrete, care was taken to insure that all steel decks were free of any foreign matter such as dirt, grease or oil. A slump test was performed before proceeding with concrete casting and vibration of the concrete was accomplished with a small laboratory needle-type vibrator. Periodically during the pour, standard test control cylinders (150 mm × 300 mm) were cast in accordance with CAN3-A23.2-M77 [4].

All specimens were stripped of formwork after three days and kept moist and covered with burlap and a plastic film until the concrete was seven days old. The specimens were then air cured for at least an additional twenty-one days until tested. The control cylinders were immersed in a curing tank for seven days, after which they were air cured.

Test Equipment and Instrumentation

All specimens were tested in a testing frame with the loading being applied by means of an MTS Electrohydraulic Servo Unit. Instrumentation for all test specimens included mechanical dial gauges (0.01 mm) for measuring vertical deflections, and to obtain a continuous load-deflection and end-slip read-out during each test, a Hewlett-Packard 7004BX-Y Recorder connected to DC displacement transducers was used.

Test Procedure

Each composite slab specimen was tested on simple span supports and subjected to a symmetrical mode of loading consisting of a two-point concentrated line load arrangement. Figure 4 shows a typical test set-up of the loading scheme used. Neoprene rubber pads were used to distribute the concentrated line loads onto the concrete in a relatively uniform manner. It was assumed that any undesirable longitudinal restraint of the test set-up was eliminated by the system of roller and pin supports acting in conjunction with the spherical bearing head of the ram unit.

After proper alignment of each specimen in the loading frame, vertical deflection dials and electrical displacement transducers were positioned and attached. Horizontal slip between concrete and steel deck (end-slip) was measured at the ends of each specimen by means of electrical displacement transducers.

Loading was applied continuously under stroke control and dial gauge readings were recorded without test interruption. Cracking characteristics, mode of failure, end-slip and ultimate load of each specimen were documented. All pertinent dimensional measurements such as width and overall concrete depth of specimen were recorded. The overall concrete depth, in particular, was measured at both ends, at the centre of span and at the major failure crack of each specimen.

TEST RESULTS

Test results are presented and discussed for both pull-out and composite slab specimens. The data are contained in tables at the end of the paper, giving for each specimen tested relevant measured and computed information. In particular, Table 1 gives the mechanical properties of the steel used in the pull-out and composite slab tests. Experimental data and results of the pull-out tests are summarized in Table 2, and for composite slab tests, in Table 3 (symbols are defined at the end of the paper).

Pull-Out Tests

Table 2 summarizes both the load at first slip and the ultimate experimental load. These loads are divided by the adhesion surface area, and the average of two duplicate specimens is shown. The ZF075 wiped coat oiled specimens exhibited the lowest load at the point of first slip, therefore, the bond strengths for all the other materials were normalized relative to the ZF075 wiped coat oiled value. To do this, each $(P_s/A_{ad})_{avg}$ value was divided by the ZF075 wiped coat oiled value to produce the R_{wo} factors presented in the table.

The R_{wo} values are also presented graphically in Figure 5. It can be seen that the cold rolled (uncoated), ZF075 wiped coat and Z275 galvanized steel all exhibited higher bond strengths with their adhesion surfaces cleaned, than with a slushing oil applied. For these three coatings, the improvement due to cleaning was: cold rolled (uncoated)--57%, ZF075 wiped coat--266%, and Z275 galvanized--80%. However, the AZ150

Galvalume steel in each of the four surface conditions outperformed all of the other coatings tested. Also, the improvement due to cleaning was only 6%, which reflects the consistently high bond strengths observed for the AZ150 Galvalume steel.

Composite steel deck is normally used without any oil applied to the surface. Therefore, more useful information is obtained by comparing the bond strengths of the cleaned specimens. Each $(P_s/A_{ad})_{avg}$ value was divided by the wiped coat cleaned value to produce the R_{wc} factors presented in the table. It can be seen that the Z275 galvanized had a 6% weaker bond strength than the ZF075 wiped coat, while the AZ150 Galvalume had a 27% stronger bond strength than the ZF075 wiped coat. Therefore, the cleaned AZ150 Galvalume steel was 1.27/.94 = 35% stronger than the cleaned Z275 galvanized steel.

Of particular interest is the performance of the AZ150 Galvalume samples with lacquered surfaces. The spray lacquer effectively minimizes any reaction between the metallic coating and the concrete, yet the bond strength was not significantly lower than that of the cleaned AZ150 Galvalume sample. Other pull-out tests on epoxy and paint coatings [5,6] indicated, rather surprisingly, that epoxy coatings with glossy finishes produced higher bond strengths than flat primers. Therefore, a smooth, glossy surface does not necessarily result in a poor bond with concrete.

Coating effects of steel floor decks were also investigated in Reference 7. An enamel paint coating on Z275 galvanized exhibited a higher bond strength than Z275 galvanized when unembossed steel decks were used. However, the reverse was true when embossed decks were tested. Therefore, the interaction between the concrete and the steel deck can not be completely explained by the deck's surface treatment alone.

Typical load versus cross-head travel curves are shown in Figure 6. Each of the twenty pull-out tests can be approximated by one of the three curves. Curve 1, where the load increased, then levelled off, and finally fell off as the specimen was extracted, was most common. In some cases (curves 2 and 3) the load fell off after the point of first slip and then recovered as the specimen was extracted from the concrete. This recovery was either less than the first slip load, curve 2, or greater than the first slip load, curve 3. All of the AZ150 Galvalume coated specimens approximated curve 1, as did the ZF075 wiped coat cleaned specimens. The cold rolled (uncoated) specimens typically exhibited curve 2 behaviour. The ZF075 wiped coat oiled and Z275 galvanized specimens tended to follow curve 3. Part of the reason for the load recovery in curves 2 and 3 can be attributed to the increase in cross-head speed after the point of first slip was detected. The higher pulling rate is expected to result in a higher load.

Composite Slab Tests

The description of the failure mode was based on the actual laboratory test results obtained in this investigation. Only one distinct mode of failure was experienced, namely, shear-bond with early end-slip. The characterization of this failure at ultimate load, for both AZ150 Galvalume and

Z275 galvanized specimens, was identified by the formation of a major crack under or near one of the line loads, resulting in failure accompanied by early end-slip, and causing the concrete shear span portion, L', to lose its composite action with the steel deck. Figure 7 shows a photograph of a typical shear-bond failure crack. At no time, however, did the concrete shear span portion become disengaged from the steel deck; i.e., the mechanical shear transfer devices of the deck, even after ultimate load was reached, prevented the system from becoming undone. The ultimate shear-bond resistance was taken as the largest load attained by the specimen. The characterization of both AZ150 Galvalume and Z275 galvanized specimens failing in shear-bond is similar to other embossment-type systems failing in the same mode as reported in References 1, 8, 9, 10 and 11.

Considering the average ultimate load of the AZ150 Galvalume specimens (96.0 kN) and the average of the Z275 galvanized specimens (72.6 kN), as summarized in Table 3, the AZ150 Galvalume specimens experienced a 32% increase in ultimate load in comparison with the Z275 galvanized specimens. It is interesting to note that the ultimate load (shear-bond), interpolated from a previous proprietary study carried out by R.M. Schuster on the Lorlea D-900C composite deck using ZF075 wiped coat galvanized steel, was 92.7 kN. This indicates that the AZ150 Galvalume specimens also experienced larger ultimate loads in comparison with the ZF075 wiped coat surface condition. It has been known that ZF075 wiped coating performs better than Z275 galvanized coating, at least based on unembossed steel deck slab tests reported by Porter and Ekberg [7]. This has also been confirmed in the pull-out tests discussed above. Reference 7 contains only limited results on embossed (composite) slab tests, with only enamelled and galvanized coating surface comparisons, indicating that the galvanized coating results in a 9.5% increase in ultimate load in comparison to the enamelled coating condition.

Concerning load-deflection and end-slip behaviour, both AZ150 Galvalume and Z275 galvanized specimens behaved in a similar manner as other composite slabs exhibiting early end-slip [9,11]. Three distinct stages of load-deflection behaviour were identified with all six specimens, namely, 1) the uncracked stage, 2) the cracked or initial end-slip stage, and 3) the stage of apparent yielding of the steel deck.

For the purpose of illustration, the load-deflection behaviour of AZ150 Galvalume specimen 3 and Z275 galvanized specimen 6 are shown in Figure 8. As can be observed from Figure 8, both specimens were identical in behaviour up to and through the initial end-slip stage, however, beyond this stage the AZ150 Galvalume specimen exhibited a greater stiffness and ultimate load in comparison to the Z275 galvanized specimen. Both specimens reached a flat plateau at ultimate, indicating that yielding in the bottom of the steel deck had occurred. This behaviour was typical for all the other composite slab specimens tested.

CORROSION RESISTANCE OF METALLIC COATINGS

Following the structural tests on the composite slabs, an AZ150 Galvalume and a Z275 galvanized steel deck were separated from the concrete and visually inspected for corrosion attack. Both coated steels had the same nominal coating thickness per side of 0.02 mm (0.8 mils) and both exhibited some loss of coating. The apparent chemical interaction between the concrete and the AZ150 Galvalume coating appeared to be more extensive than that of the Z275 galvanized coating. Also, some concrete adhered to the AZ150 Galvalume surface while the Z275 galvanized surface was essentially free of concrete. This indicates a better bond between AZ150 Galvalume and concrete than between Z275 galvanized and concrete, which is also reflected in the appearance of the concrete surface after separation from the steel decks. The concrete that was separated from the AZ150 Galvalume deck was rough (Figure 9), while the concrete from the Z275 galvanized deck was smooth (Figure 10).

Representative sample disks were punched from six locations across the width of the composite deck for each of the two coatings. The initial coating weight per unit area was established from sample disks taken across the width of portions of floor deck which were not covered with concrete. A second set of disks was punched from the decks used in the slab tests. Any concrete adhering to the disk was first removed with a chromic acid cleaning solution, then each disk was weighed both before and after the metallic coating on the exposed surface was stripped. This allowed the determination of the metallic coating weight per unit area which remained on the surface of each steel deck exposed to concrete. By comparing the exposed to the unexposed coating weight, a percent coating loss was calculated. These results are summarized in Table 4. It can be seen that the AZ150 Galvalume lost 50% of the metallic coating weight on the surface exposed to the concrete, while the Z275 galvanized coating weight loss was 8%.

In addition to the coating weight investigation, the exposed surfaces were examined under a microscope. Figure 11 shows a photomicrograph at approximately 18X magnification of the AZ150 Galvalume coated surface after the adhering concrete was stripped. The lighter areas are the AZ150 Galvalume coating and the dark areas are the base steel. In some areas the AZ150 Galvalume coating was completely gone, exposing the base steel. However, absolutely no pitting of the base steel was detected. Figure 12 shows a similar photomicrograph of the Z275 galvanized surface. The Z275 galvanized coating also exposed small areas of the base steel, although to a lesser extent than in the case of the AZ150 Galvalume coating. Again, no pitting of the base steel was detected.

To determine the uniformity of coating attack, samples were taken across the width of the exposed deck specimens. Figures 13 and 14 are cross-sectional photomicrographs of the AZ150 Galvalume and Z275 galvanized samples, respectively, taken at approximately 200X magnification. The gray area is the base steel and the metallic coating appears as the lighter area. These figures confirm that some areas of base steel are no longer covered by the metallic coating and that no base steel attack has occurred.

CONCLUSIONS

(1) The adhesion bond strength between AZ150 Galvalume steel and concrete is on average 32% greater than that of Z275 galvanized steel.

(2) The adhesion bond strength between AZ150 Galvalume steel and concrete is greater than that of ZF075 wiped coat galvanized steel.

(3) Although the coating loss was greater for the AZ150 Galvalume steel than the Z275 galvanized steel, no base steel attack was encountered with either material.

(4) AZ150 Galvalume steel is an acceptable material for composite floor deck in applications where water will not penetrate the concrete to the top surface of the steel deck and chloride contamination is avoided. The traditional advantages of AZ150 Galvalume steel remain, of course, for the underside of the composite floor deck.

ACKNOWLEDGEMENT

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DEFINITIONS

Symbol	Definition
A_{ad}	Adhesion surface area of pull-out test, mm^2
A_s	Cross-sectional area of steel in pull-out test, mm^2
B	Width of composite slab specimen, mm
D	Overall depth of composite slab section, mm
f'_c	Compressive strength of concrete in slab tests, MPa
F_y	Yield strength of steel in pull-out test, MPa
L	Length of span of composite slab, mm
L'	Length of shear span of composite slab, mm
P_e	Experimental composite slab load, kN
P_{is}	Experimental initial end-slip load of composite slab, kN
P_s	Experimental load at first slip of pull-out test, kN
P_u	Ultimate experimental load of pull-out test, kN
P_{ut}	Ultimate experimental load of composite slab test, kN
R_{wo}	Ratio of $(P_s/A_{ad})_{avg}$ divided by 164 kPa (ZF075-0)
R_{wc}	Ratio of $(P_s/A_{ad})_{avg}$ divided by 601 kPa (ZF075-C)
t_c	Coated steel deck thickness, mm
Wiped Coat	A hot-dip, zinc-coated product that is wiped after the strip emerges from the zinc pot to produce a fully alloyed zinc-iron coating. The coating can also be produced by heat treating, i.e., galvannealing.

TABLES

Table 1 Mechanical Steel Properties of Pull-out and Composite Slab Tests

Mechanical Properties	Coating Condtion					
	Pull-Out Tests				Composite Slab Tests	
	C.R.	WIPED	Z275	AZ150	Z275	AZ150
Core Thickness (mm)	1.47	1.55	1.45	1.55	0.930*	0.949*
Yield Strength (MPa)	228	287	274	306	282	299
Tensile Strength (MPa)	314	368	334	362	379	367
Percent Elongation in 50 mm Gauge Length	39.9	34.2	36.0	32.6	29.9	26.1

NOTE: Values in table are averages of two tensile coupon tests for each coating.

*Coated steel thickness

TABLE 2 Experimental Data and Results of Pull-Out Tests

Specimen No.	Coating and* Surface Cond.	$A_{ad} \times 10^3$ (mm^2)	P_s (kN)	P_s/A_{ad} (kPa)	{Avg. (kPa)	P_u (kN)	P_u/A_{ad} (kPa)	{Avg. (kPa)	P_u/A_s (MPa)	F_y (MPa)	R_{wo}	R_{wc}
1	C.R.-O	31.5	6.45	205	325	9.88	314	379	125	228	1.98	0.54
2		31.5	14.0	445		14.0	445		175			
3	ZF075-O	31.4	5.34	170	164	7.87	251	261	98.6	287	1.00	0.27
4		31.4	4.98	158		8.54	272		107			
5	Z275-O	31.4	13.4	425	314	16.2	515	634	206	274	1.92	0.52
6		31.4	6.41	204		23.6	752		301			
7	AZ150-O	31.3	23.3	743	719	26.4	844	839	312	306	4.38	1.20
8		31.4	21.8	695		26.2	834		308			
9	C.R.-C	31.5	16.5	522	508	21.8	691	692	272	228	3.10	0.85
10		31.5	15.6	494		21.8	692		272			
11	ZF075-C	31.4	16.6	530	601	16.6	530	641	209	287	3.66	1.00
12		31.5	21.1	672		23.6	751		295			
13	Z275-C	31.3	19.1	611	567	24.4	778	743	311	274	3.45	0.94
14		31.4	16.5	524		22.3	709		283			
15	AZ150-C	31.3	24.0	769	765	28.6	915	914	338	306	4.66	1.27
16		31.2	23.8	762		28.5	912		336			
17	AZ150-V	31.3	25.4	809	796	28.2	899	877	332	306	4.85	1.32
18		31.0	24.2	783		26.5	855		316			
19	AZ150-L	31.2	23.6	755	751	27.7	886	889	327	306	4.58	1.25
20		31.3	23.4	747		27.9	892		330			

*Key:
C.R. - Cold rolled steel (uncoated)
ZF075 - Wiped coat galvanized steel
Z275 - Galvanized steel
AZ150 - Galvalume steel

O - Slushing oil
C - Cleaned
V - Vanishing Oil
L - Lacquered

Table 3 Experimental Data and Results of Composite Slab Tests

Specimen No.	L (mm)	B (mm)	D (mm)	L' (mm)	f'_c* (MPa)	P_{is} (kN)	P_{ut} (kN)	Mode of Failure
(AZ150) Galvalume								
1	2400	900	143	600	26.5	44.2	94.2	Shear-Bond
2	2400	900	140	600	26.5	43.9	94.5	Shear-Bond
3	2400	900	142	600	26.5	50.4	99.2	Shear-Bond
							96.0**	
(Z275) galvanized								
4	2400	900	140	600	26.5	49.2	74.0	Shear-Bond
5	2400	895	140	600	26.5	49.0	66.9	Shear-Bond
6	2400	900	140	600	26.5	51.6	76.8	Shear-Bond
							72.6**	

*Average of 6 test cylinders; **Average of 3 tests

Table 4 Weight Loss of Metallic Coatings After Exposure to Concrete (average of six measurements)

Coating Type	Initial Coating Weight (g/m^2)	Coating Weight After Exposure (g/m^2)	Coating Weight Loss (%)
(AZ150) Galvalume	93	47	50
(Z275) galvanized	130	120	8

FIGURES

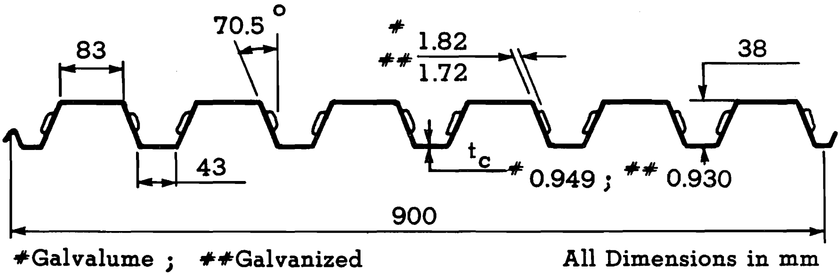

Figure 1 Typical Geometric Profile of the D-900C Composite Steel Deck (average dimensions are shown)

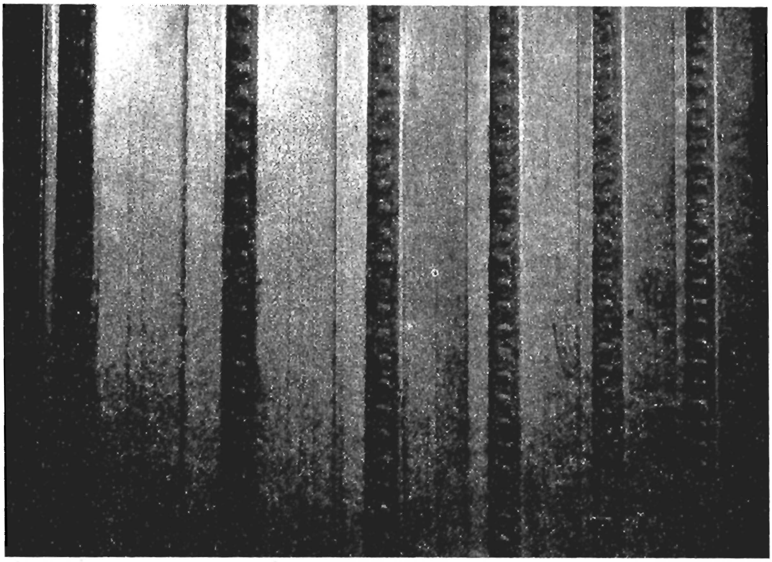

Figure 2 Photograph Showing Galvalume Coated D-900C Composite Deck

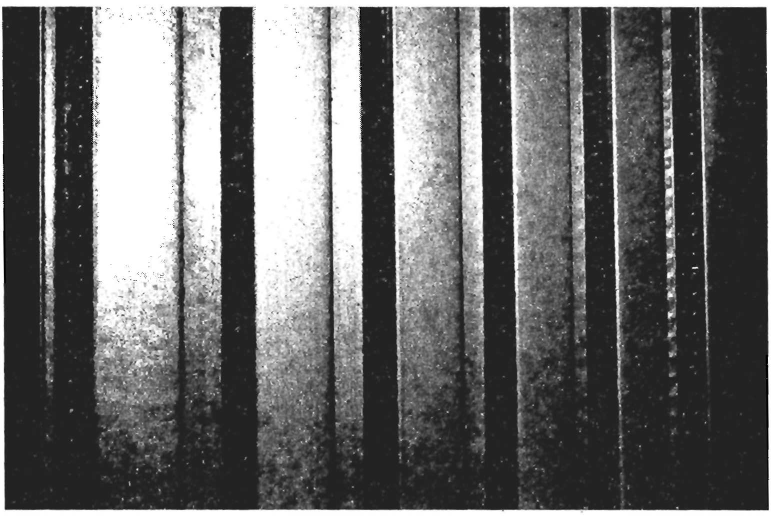

Figure 3 Photograph Showing Galvanized Coated D-900C Composite Deck

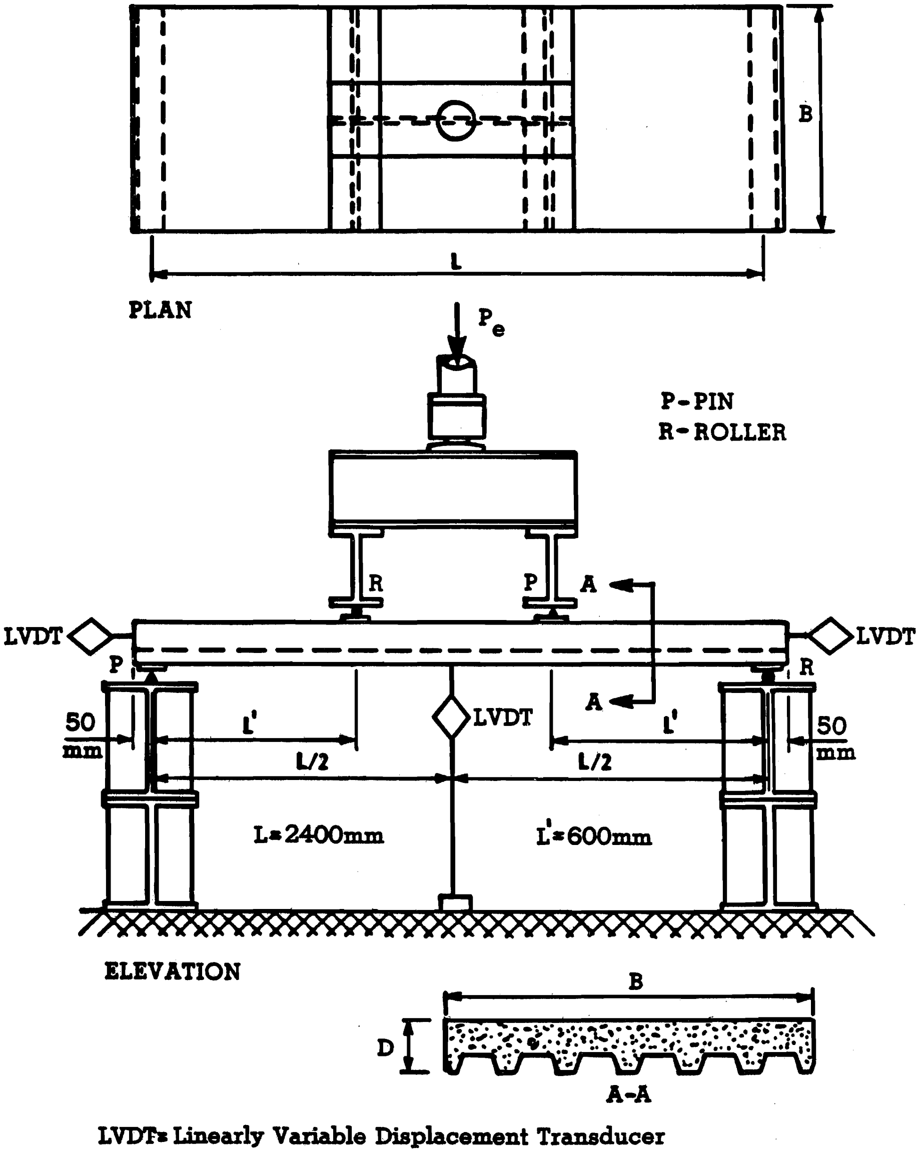

Figure 4 Schematic of Composite Slab Test Set-Up

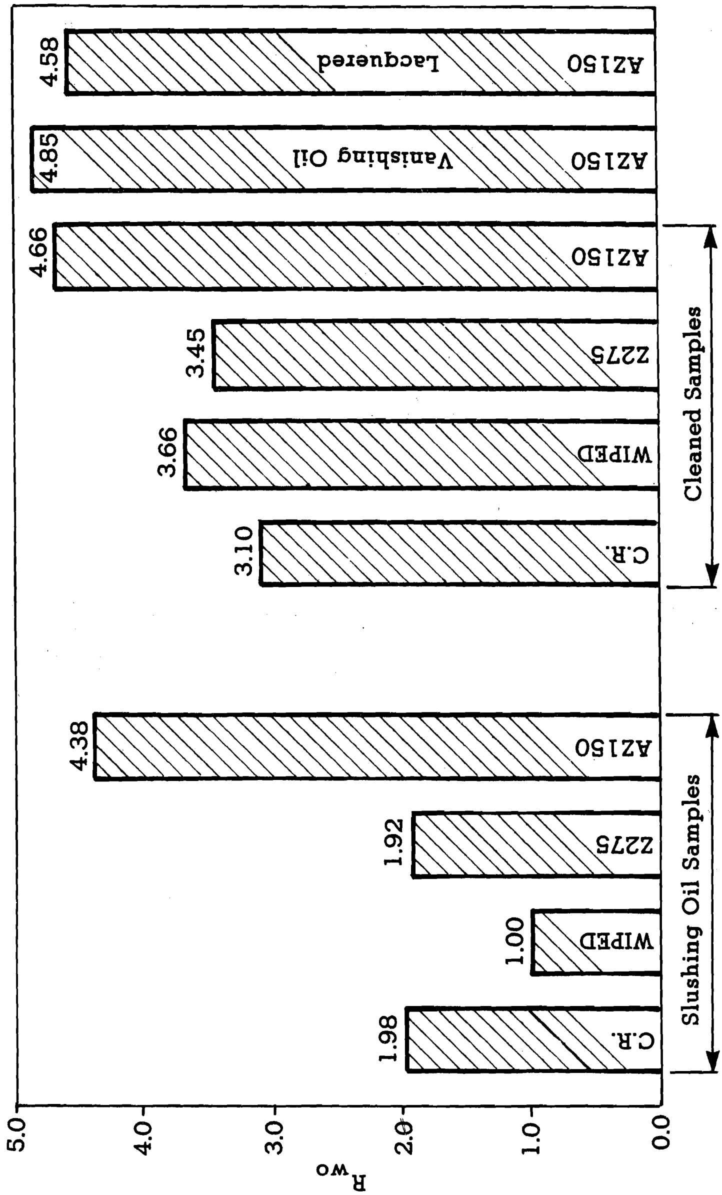

Figure 5 Summary of Relative Pull-Out Test Performances

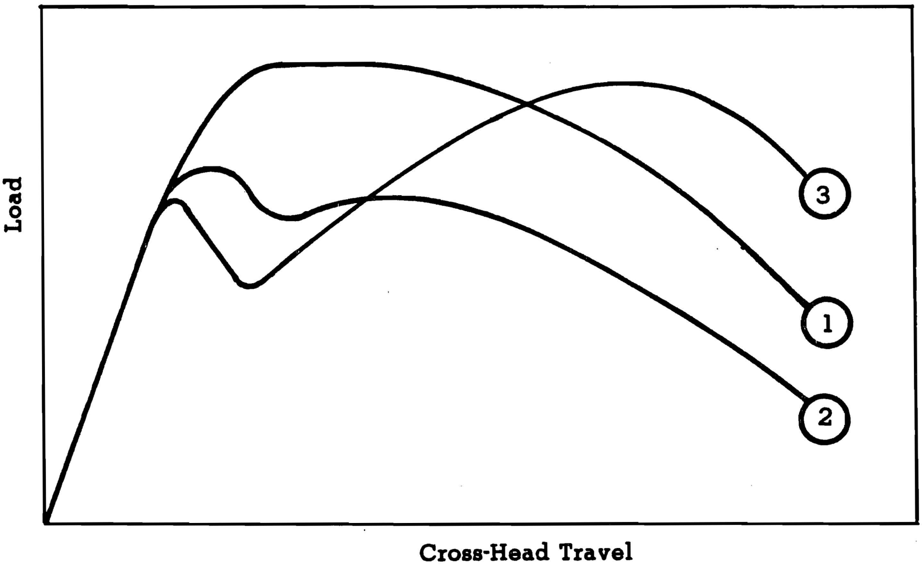

Figure 6 Typical Load vs. Cross-Head Travel Curves of Pull-Out Tests

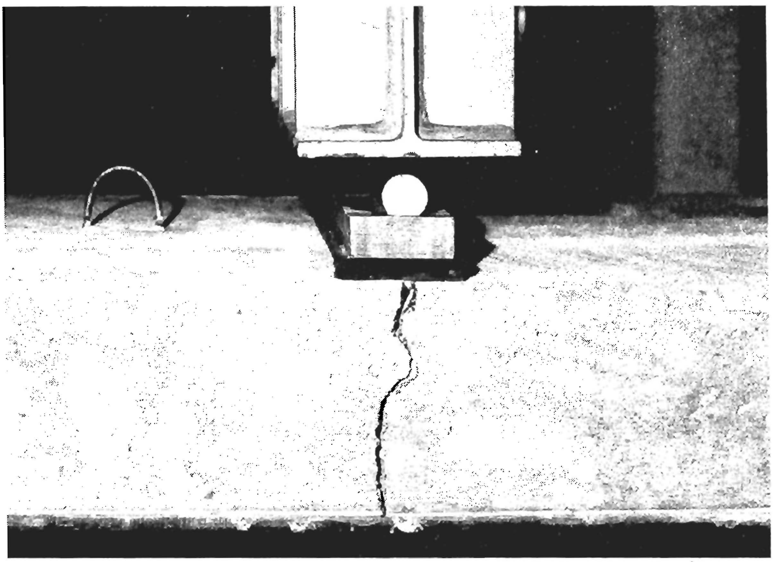

Figure 7 Photograph Showing Typical Shear-Bond Failure Crack

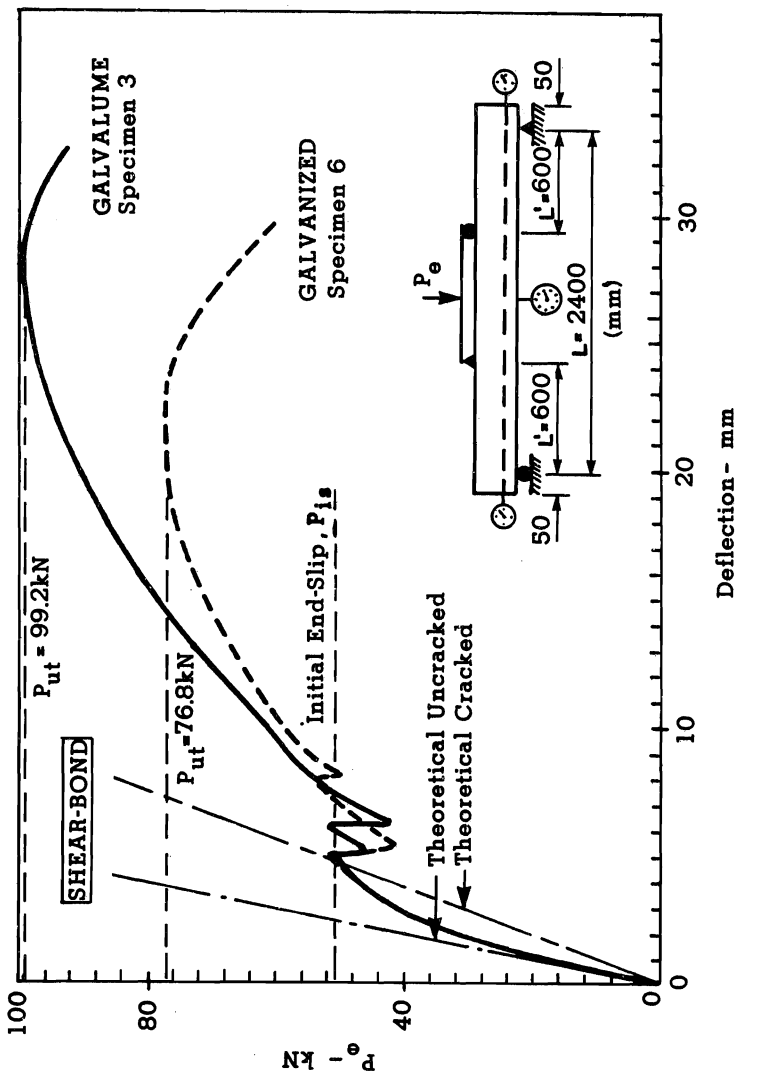

Figure 8 Load Deflection Curves of Composite Slab Specimens 3 and 6

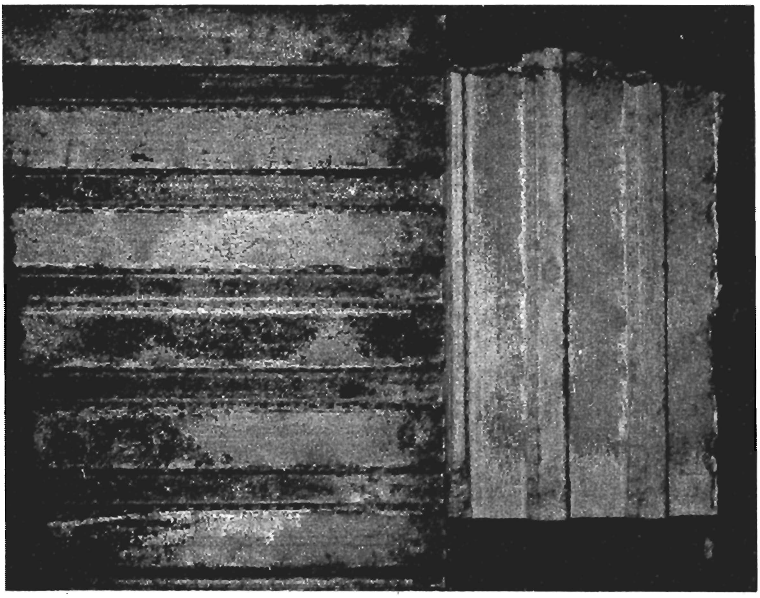

Figure 9 Photograph Showing Surface Condition of Galvalume Composite Slab (Top--Steel Deck; Bottom--Concrete)

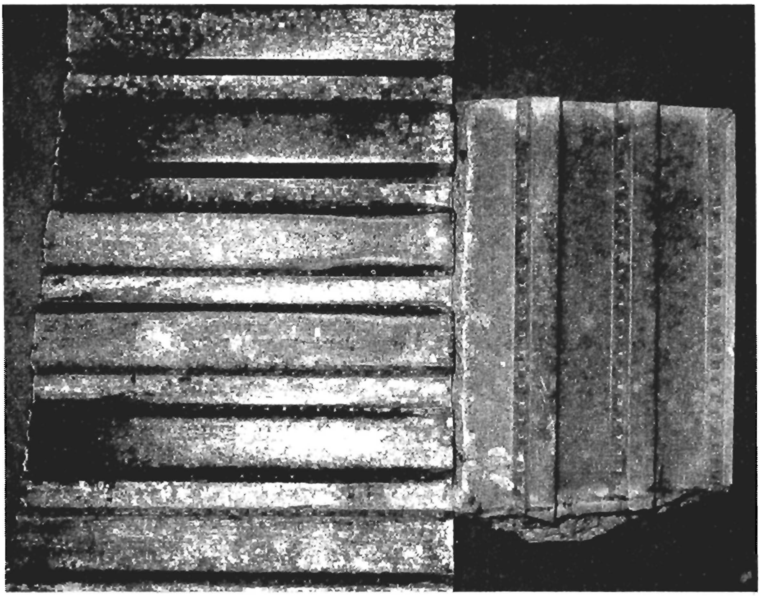

Figure 10 Photograph Showing Surface Condition of Galvanized Composite Slab (Top--Steel Deck; Bottom--Concrete)

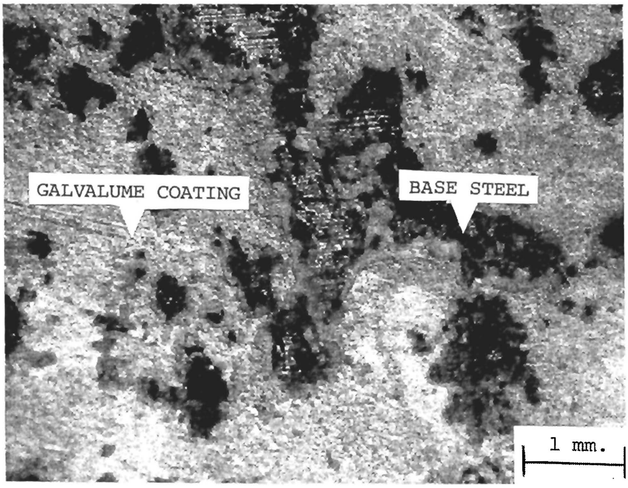

Figure 11 Photomicrograph of Galvalume Steel Surface After Exposure to Concrete

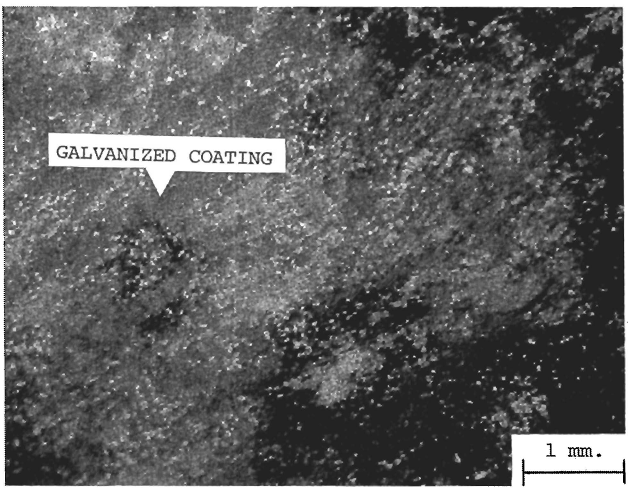

Figure 12 Photomicrograph of Galvanized Steel Surface After Exposure to Concrete

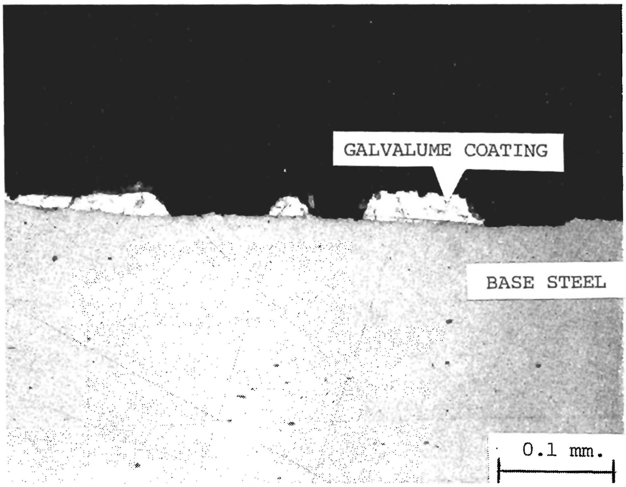

Figure 13 Cross-Sectional Photomicrograph of Galvalume Steel After Exposure to Concrete

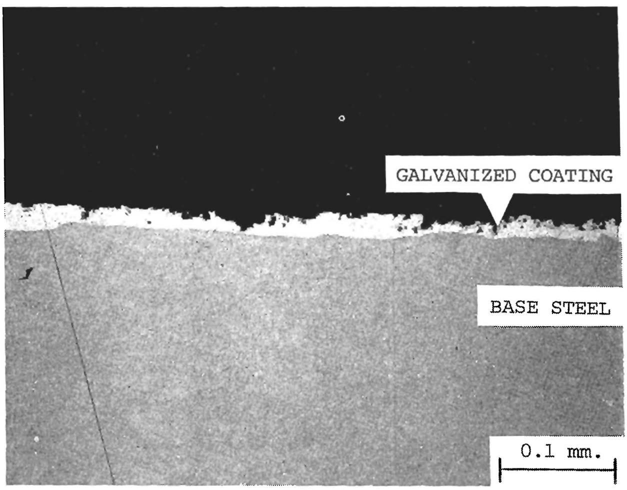

Figure 14 Cross-Sectional Photomicrograph of Galvanized Steel After Exposure to Concrete