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INSPECTION AND EVALUATION OF A BRIDGE DECK PARTIALLY REINFORCED WITH GFRP REBARS

by

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16. Abstract

The corrosion of steel can be a significant problem in bridge decks in which the reinforcing and prestressing steel are accessible to deicing salts and combinations of moisture, temperature and chlorides through cracks, leading to concrete deterioration and loss of serviceability. Fiber Reinforced Polymer (FRP) rebars have emerged as one alternative to steel reinforcement in corrosive environments.

The objective of this study is to evaluate the cracks formed on a bridge deck that is partially reinforced with glass fiber reinforced polymer (GFRP) rebars. The bridge constructed in 1997 is in Bourbon County, KY, on US460 over the Rogers' Creek. It's deck is partially reinforced with GFRP rebars in place of epoxy coated steel rebars. The bridge has been monitored for cracks over a period of two years from June 1998 to July 2000.

The maximum measured crack width of 0.013 in (0.3 mm) in the GFRP reinforced section meets the maximum allowed by ACI (Section 10.6) and AASHTO (Section 8.16.8.4) specifications in steel reinforced structures for exterior exposure.

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1.0 EXECUTIVE SUMMARY

1.1 Introduction

The corrosion of steel is a significant problem in bridge decks in which the reinforcing and prestressing steel are accessible to deicing salts and combinations of moisture, temperature and chlorides through cracks, leading to concrete deterioration and loss of serviceability. Fiber reinforced polymer (FRP) rebars have emerged as a practical alternative solution to steel reinforcement corrosion. This report documents a two and a half year period during which cracks in a bridge deck which is partially reinforced with Glass Fiber Reinforced Polymer (GFRP) rebars were monitored and evaluated.

1.2 Objective and Scope

The objective of this study is to measure and evaluate the cracks observed in a bridge deck which is partially reinforced with GFRP rebars and partially reinforced with steel rebars. The objective is achieved by carrying out the following tasks; (i) Measuring the length, width, and location of cracks in the bridge deck under loaded and unloaded conditions in the GFRP Reinforced area, (ii) Measuring the length, width, and location of cracks in the bridge deck under loaded and unloaded conditions in the steel reinforced area, and (iii) Comparing the cracks observed in the GFRP reinforced and steel reinforced areas.

1.3 Bridge Description

This particular study was carried out for the deck of the US-460 bridge over the Rogers' Creek in Bourbon County, Kentucky. The bridge is a simply supported PCI beam structure with a length of 36.5 ft (11.1 m) and width of 36.0 ft (10.97 m). The GFRP reinforced bars are placed in a region of the top reinforcing mat of size 8.9 ft x 15.5 ft (2.7 m x 4.7 m) as shown in Fig. 1.1. The remaining portion of the top reinforcing mat of the bridge deck is constructed using steel rebars.

1.4 Conclusions

In general, crack widths in the range of 0.004 in to 0.04 in (0.1 mm to 1 mm) arise primarily from temperature gradients, and shrinkage. Cracks observed in the GFRP reinforced and the steel reinforced areas are summarized as follows:

(i) The length and width of a crack observed in the top surface of GFRP reinforced area under unloaded condition is 13.6 ft and 0.003 in, respectively.

(ii) The length and width of a crack observed in the top surface of GFRP reinforced area under loaded condition is 10.0 ft and 0.013 in, respectively.

(iii) The length and width of a crack observed in the top surface of steel reinforced area under unloaded condition is 6.9 ft and 0.003 in, respectively.

(iv) The length and width of a crack observed in the top surface of steel reinforced area under loaded condition is 3.2 ft and 0.002 in, respectively.

The maximum measured crack width of 0.013 in (0.3 mm) in the GFRP reinforced section meets the maximum allowed by ACI (Section 10.6) and AASHTO (Section 8.16.8.4) specifications in steel reinforced structures for exterior exposure. Consequently, since GFRP rebars do not corrode, the ACI limits on crack width are very conservative.

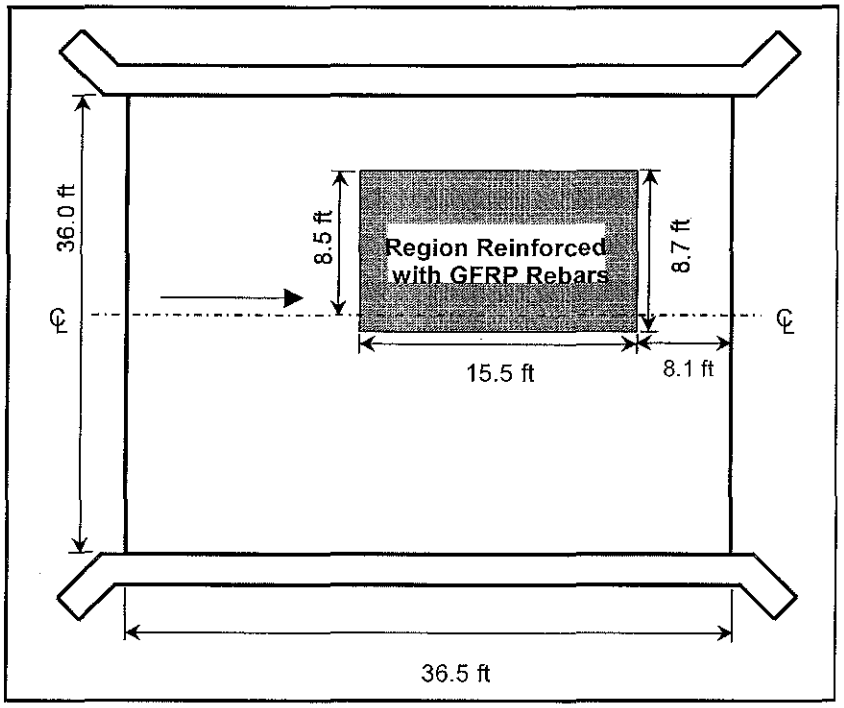


Figure 1.1. Plan View of Bridge Deck Showing the Location of the GFRP Rebars

2.0 INTRODUCTION

Cracking in bridge decks is a common problem in the United States, especially in the last 20 years. Exposure of bridge deck steel to a combination of moisture, temperature and chlorides from de-icing salts through surface cracks leads to concrete deterioration and loss of serviceability. Furthermore, water trapped in the bridge deck can freeze which in turn affect the flexural behavior of the deck, and alter the load distribution behavior (Allen 1992). Nationwide billions of dollars has been spent replacing bridge decks deteriorated by the effects of cracking.

The surface cracks predominantly occur in new bridge decks, developing shortly after construction. These cracks are typically very small, with widths ranging between 0.004 in and 0.008 in (0.1 mm and 0.2 mm), and are not visible under normal conditions. In some European Countries cracks up to a width of 0.008 in (0.2 mm) are allowed even in humid environments with the presence of deicing salts (Ducret et al., 1997). A crack width of 0.013 in (0.33 mm) is allowed in concrete decks by AASHTO (2002) and ACI 318 (2002) Specifications.

This report presents the pattern of cracks observed over a period of two years, from June 1998 to July 2000, in a bridge deck on US460 over Rogers' Creek in Bourbon County, Kentucky which is partially reinforced with Glass Fiber Reinforced Polymer (GFRP) rebars and steel rebars. Comparisons are made between the cracks observed in the GFRP reinforced area and steel reinforced area.

3.0 OBJECTIVE

The objective of this study is to measure and evaluate the cracks observed in a bridge deck which is partially reinforced with GFRP rebars and steel rebars. The bridge

over Rogers' Creek is monitored continuously for two and a half years for this purpose. The objective is achieved by carrying out the following tasks;

(i) Measuring the length, width, and location of cracks in the bridge deck under loaded and unloaded conditions in the GFRP reinforced area.

(ii) Measuring the length, width, and location of cracks in the bridge deck under loaded and unloaded conditions in the steel reinforced area.

(iii) Comparing the cracks observed in the GFRP reinforced and steel reinforced areas.

4.0 BRIDGE DESCRIPTION

This particular study is carried out for the deck of the US-460 bridge (Fig. 4.1) over Rogers' Creek in Bourbon County, Kentucky. The bridge is a simply supported PCI beam structure with a length of 36.5 ft (11.1 m) and width of 36.0 ft (10.9 m). The GFRP reinforced bars are placed in a region of the top reinforcing mat of size 8.9 ft x 15.5 ft (2.7 m x 4.7 m) as shown in Fig. 4.2. The remaining portion of the top reinforcing mat of the bridge deck is constructed using steel rebars (Deitz 1998). The lighter area of the mat close to the center of the bridge highlighted with dots is the GFRP rebar area (Fig. 4.3).

5.0 FIELD MONITORING

After construction of the bridge, the deck has been continuously monitored for cracks over a period of two and a half years on an average of once in every month. The monitoring procedure involved;

(i) Checking the top and bottom surfaces of the deck for cracks under loaded and unloaded conditions.

(ii) Measuring crack width and length on top and bottom surfaces of GFRP reinforced area.

(iii) Measuring crack width and length on top surface of steel reinforced area.

(iv) Measuring ambient environmental conditions.

The following procedure was adopted to measure the cracks on the top and bottom surfaces of the deck.

Before checking the deck surfaces for cracks the traffic on both sides of the bridge is closed. The overall condition of the bridge is observed. A detailed inspection of the bridge deck is performed manually with the use of a magnifying glass (Fig. 5.1). The observed crack width is measured using crack gauges, and crack length is measured using steel tapes.

The locations of the cracks are noted based on grid markings over the GFRP and steel reinforced areas. In the GFRP reinforced area, the x-axis of the grid is marked from No. 1 to No. 16 and the y-axis is marked from A to I (Fig. 5.2). In the steel reinforced area, the x-axis is marked from No. 16 to No. 1 and the y-axis is marked from A to I (Fig. 5.3).

6.0 MEASUREMENT OF CRACKS UNDER LOADED AND UNLOADED CONDITIONS

The length, width and propagation of cracks in the GFRP and steel reinforced areas are noted for the no load condition on the top and bottom surface of the bridge deck (Figs. 6.1 and 6.2). Crack measurements are shown in Table 1 to Table 3.

Similar crack measurements were made with the deck loaded by a standard truck with a wheel load of 20 kips positioned at a predefined location of the bridge (Fig. 6.3). The position of the wheel load was selected to produce flexural effects in both GFRP

reinforced and steel reinforced grids. Crack measurements for the loaded conditions are also shown in Table 1 to Table 3.

The length, width and location of cracks observed in the top and bottom surfaces of the bridge deck during loaded and unloaded conditions for the GFRP reinforced area are also shown in Figs. A1 to A41 (Appendix A). The length, width and location of cracks observed in the top and bottom surfaces of the bridge deck under loaded and unloaded conditions for the steel reinforced areas are shown in Figs. B1 to B10 (Appendix B). The temperature and relative humidity at the time of each inspection are shown in Table 1 to Table 7.

7.0 EVALUATION

All the cracks observed in the GFRP reinforced area were numbered. The details of the cracks observed in the top surface of the bridge deck for loaded and unloaded conditions are shown in Table 4 to Table 7 and those in the bottom surface of the bridge deck for loaded and unloaded conditions are shown in Table 8.

Cracks observed in the top surface of the steel reinforced area were also numbered and the details of these cracks observed during loaded and unloaded conditions are shown in Table 9 to Table 19. Crack widths and lengths, along with the associated date of observation, temperature, and relative humidity are plotted (Figs. 7.1 to 7.5) for the entire monitoring period facilitating comparison of the data collected from the top and bottom surfaces of the bridge deck for both GFRP reinforced and steel reinforced areas.

8.0 CONCLUSIONS

In general, crack widths in the range of 0.004 in to 0.04 in (0.1 to 1 mm) arise primarily from temperature gradients, moisture content, and chemical corrosion such as

corrosion of reinforcement and alkali-aggregate reaction (Kumar Mehta 1997). Cracks observed in the GFRP reinforced and the steel reinforced areas are summarized as follows:

(i) The length and width of a crack observed on the top surface of GFRP reinforced area under unloaded condition is 13.6 ft and 0.003 in, respectively.

(ii) The length and width of a crack observed on the top surface of GFRP reinforced area under loaded condition is 10.0 ft and 0.013 in, respectively.

(iii) The length and width of a crack observed on the top surface of steel reinforced area under unloaded condition is 6.9 ft and 0.003 in, respectively.

(iv) The length and width of a crack observed on the top surface of steel reinforced area under loaded condition is 3.2 ft and 0.002 in, respectively.

The maximum measured crack width of 0.013 in (0.3 mm) in the GFRP reinforced section meets the maximum allowed by ACI (section 10.6) and AASHTO (section 8.16.8.4) specifications in steel reinforced structures for exterior exposure.

Table 1. Summary of Cracks Observed in the Top Surface of the Bridge Deck from 6/19/98 to 3/17/2000 Within GFRP Reinforced Area

Date	Temp	Relative Humidity	Crack No	No Loading on Bridge			Truck Load on Bridge		
				Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
	(^{0}F)	(%)							
06/19/1998	91	75	1	0.003	2.5	I,8-10			
06/26/1998	95	100	1	0.002	2.5	I,8-9			
06/26/1998	95	100	2	0.001	2.3	I,15			
08/11/1998	70	100	1	0.002	2.0	I,8-9			
08/11/1998	70	100	2	0.003	1.0	I,15			
08/11/1998	70	100	3	0.002	2.0	A,6	0.002	2.0	A,6
09/08/1998	70	40	2	0.003	1.0	I,15			
09/08/1998	70	40	3	0.002	2.5	A,6			
09/08/1998	70	40	4	0.002	2.5	I,14			
10/16/1998	57	80	2	0.002	1.5	I,15			
10/16/1998	57	80	3	0.002	3.0	A,6			
10/16/1998	57	80	5	0.003	0.5	D,15			
10/16/1998	57	80	6	0.005	1.3	F,14			
12/04/1998	68	50	7	0.002	48.0	E,5-9			
12/04/1998	68	50	8	0.002	6.0	E,4-5			
12/04/1998	68	50	9	0.002	7.5	E,3-4			
12/04/1998	68	50	10	0.002	6.3	E,2-3			
12/18/1998	45	40	11	0.003	120.0	E,1-10			
03/05/1999	38	45	11	0.002	120.0	E,1-8			
04/16/1999	40	50	11	0.003	120.0	E,1-12	0.001	120.0	E,1-12
04/16/1999	40	50	12	0.002	1.5	H,14-15			
05/28/1999	75.2	36	11	0.005	120.0	F,1-10			

Table 1. Continued...

Date	Temp (^{0}F)	Relative Humidity (%)	Crack No	No Loading on Bridge			Truck Load on Bridge		
				Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
05/28/1999	75.2	36	2	0.003	1.5	I,15			
05/28/1999	75.2	36	1	0.002	2.5	I,8			
05/28/1999	75.2	36	1	0.009	1.0	I,10			
05/28/1999	75.2	36	13	0.005	8.0	C,3			
05/28/1999	75.2	36	14	0.002	3.5	C,8			
05/28/1999	75.2	36	15	0.002	1.5	A,10			
05/28/1999	75.2	36	16	0.002	2.5	C,12			
05/28/1999	75.2	36	17	0.002	5.0	H,10-11			
06/25/1999	79.9	59	11	0.005	102.0	E,1-9			
06/25/1999	79.9	59	1	0.002	4.0	I,9-10			
06/25/1999	79.9	59	2	0.002	2.5	I,15			
06/25/1999	79.9	59	12	0.002	1.8	H,14			
06/25/1999	79.9	59	13	0.003	27.0	C-F,3			
07/21/1999	74.3	88.8	11	0.003	163.0	E,1-15			
07/21/1999	74.3	88.8	13	0.007	58.5	C-I,3			
07/21/1999	74.3	88.8	1	0.002	33.0	I,6-8			
07/21/1999	74.3	88.8	18	0.002	2.8	A,13			
07/21/1999	74.3	88.8	19	0.002	6.0	A,12			
07/21/1999	74.3	88.8	20	0.003	7.8	B,9			
07/21/1999	74.3	88.8	16	0.001	6.5	C,12			
07/21/1999	74.3	88.8	5	0.002	5.3	D,15			
07/21/1999	74.3	88.8	21	0.005	7.5	D,12-13			
07/21/1999	74.3	88.8	22	0.003	8.8	E,5			
07/21/1999	74.3	88.8	23	0.002	6.0	E,6			
07/21/1999	74.3	88.8	24	0.001	1.0	G,1			

Table 1. Continued...

Date	Temp (^{0}F)	Relative Humidity (%)	Crack No	No Loading on Bridge			Truck Load on Bridge		
				Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
07/21/1999	74.3	88.8	25	0.002	3.0	H,1-2			
07/21/1999	74.3	88.8	26	0.002	3.0	H,5			
07/21/1999	74.3	88.8	27	0.002	3.0	I,11			
07/21/1999	74.3	88.8	28	0.002	4.0	I,11-12			
07/21/1999	74.3	88.8	29	0.002	9.0	I,16			
08/23/1999	94.6	36.9	11	0.003	115.0	E,1-12			
08/23/1999	94.6	36.9	30	0.002	5.5	B,4			
08/23/1999	94.6	36.9	31	0.002	5.0	B,5			
08/23/1999	94.6	36.9	32	0.002	5.0	C,3			
08/23/1999	94.6	36.9	33	0.002	3.0	C,5			
08/23/1999	94.6	36.9	8	0.002	1.0	E,4			
08/23/1999	94.6	36.9	24	0.005	1.5	G,1			
08/23/1999	94.6	36.9	26	0.003	1.5	H,5			
08/23/1999	94.6	36.9	34	0.002	2.0	H,8			
08/23/1999	94.6	36.9	12	0.002	6.0	H,12-13			
08/23/1999	94.6	36.9	35	0.007	1.5	I,1			
10/01/1999	75.2	52	11	0.007	116.0	E,1-10	0.009	116.0	E,1-10
10/01/1999	75.2	52	32	0.002	4.0	C,3			
10/01/1999	75.2	52	24	0.003	0.5	G,1			
10/01/1999	75.2	52	1	0.003	2.5	I,8-9			
10/01/1999	75.2	52	12	0.002	4.0	H,12			
10/01/1999	75.2	52	34	0.002	1.5	H,8			
10/01/1999	75.2	52	35	0.003	1.0	I,1			
11/18/1999	68	18.3	11	0.005	106.0	E,1-10			
11/18/1999	68	18.3	32	0.002	10.0	C,3			

Table 1. Continued...

Date	Temp	Relative Humidity	Crack No	No Loading on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)		Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
11/18/1999	68	18.3	12	0.002	9.0	H,14			
12/09/1999	62.8	44.5	11	0.005	112.0	E,1-10	0.013	112.0	E,1-10
12/09/1999	62.8	44.5	36	0.002	2.0	I,4			
12/09/1999	62.8	44.5	20	0.002	5.0	B,9			
02/25/2000	65.5	58	11	0.003	106.0	E,1-10			
02/25/2000	65.5	58	5	0.002	20.0	D,16			
03/17/2000	38.3	42	11	0.005	120.0	E,1-12	0.013	120.0	E,1-12
03/17/2000	38.3	42	37	0.002	42.0	C,12-16	0.002	42.0	C,12-16
03/17/2000	38.3	42	16	0.002	7.0	C,11	0.002	7.0	C,11
03/17/2000	38.3	42	38	0.002	20.0	D,8-9	0.002	15.0	D,8-9
03/17/2000	38.3	42	30	0.002	7.5	B,4	0.002	7.5	B,4

Table 2. Summary of Cracks Observed in the Bottom Surface of the Bridge Deck from 6/19/98 to 7/10/2000 Within GFRP Reinforced Area

Date	Temp	Relative Humidity	Crack No	No Load on Bridge			Truck Load on Bridge		
				Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
	(^{0}F)	(%)							
06/19/1998	91	75	1	0.007	64.0	E,3-8			
06/26/1998	95	100	1	0.005	64.0	E,3-8	0.007	64.0	E,3-8
08/11/1998	70	100	1	0.005	64.0	E,3-8	0.007	64.0	E,3-8
09/08/1998	70	40	1	0.005	76.5	E,3-8			
12/18/1998	45	40	1	0.003	64.0	E,3-8			
04/16/1999	40	50	1	0.003	64.0	E,3-8	0.007	64.0	E,3-8
05/28/1999	75.2	36	1	0.002	64.0	E,3-8			
06/25/1999	79.9	59	1	0.005	102.0	E,3-8			
07/21/1999	74.3	88.8	1	0.005	104.0	E,3-8	0.005	104.0	E,3-8
08/23/1999	94.6	36.9	1	0.002	94.5	E,3-8			
10/01/1999	75.2	52	1	0.003	192.0	E,1-16	0.003	192.0	E,1-16
10/01/1999	75.2	52	2	0.002	10.0	B,9	0.002	10.0	B,9
10/01/1999	75.2	52	3	0.002	30.0	B,13-15	0.002	30.0	B,13-19
10/01/1999	75.2	52	4	0.003	14.0	E,8-9	0.005	14.0	E,8-9
11/18/1999	68	18.3	1	0.002	192.0	E,1-16			
12/09/1999	62.8	44.5	1	0.002	192.0	E,1-16	0.005	192.0	E,1-16
07/10/2000	100.8	42.22	1	0.003	120.0	E,1-10			
07/10/2000	100.8	42.22	5	0.002	5.0	E,13			
07/10/2000	100.8	42.22	6	0.002	6.0	H,14			

Table 3. Summary of Cracks Observed in the Top Surface of the Bridge Deck from 8/23/99 to 7/10/2000 Within Steel Reinforced Area

Date	Temp	Relative Humidity	Crack No	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)		Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
08/23/1999	94.6	36.9	1	0.002	4.0	B,12-11			
08/23/1999	94.6	36.9	2	0.002	8.0	B,8-7			
08/23/1999	94.6	36.9	3	0.001	2.0	B,7			
08/23/1999	94.6	36.9	4	0.002	2.0	D,14-13			
08/23/1999	94.6	36.9	5	0.002	33.0	D,9-7			
08/23/1999	94.6	36.9	6	0.003	54.0	D,5-1			
08/23/1999	94.6	36.9	7	0.003	3.0	F,14			
08/23/1999	94.6	36.9	8	0.002	16.0	F,12-11			
08/23/1999	94.6	36.9	9	0.002	55.0	F,9-4			
08/23/1999	94.6	36.9	10	0.005	8.0	F,1			
08/23/1999	94.6	36.9	11	0.002	4.0	G,15-14			
08/23/1999	94.6	36.9	12	0.002	32.0	H,7-4			
08/23/1999	94.6	36.9	13	0.003	82.5	H,7-1			
08/23/1999	94.6	36.9	14	0.002	20.0	I,12-9			
10/01/1999	75.2	52.7	1	0.002	6.0	B,13			
10/01/1999	75.2	52.7	1	0.002	2.0	B,11			
10/01/1999	75.2	52.7	3	0.002	6.0	B,7			
10/01/1999	75.2	52.7	15	0.002	2.0	B,4			
10/01/1999	75.2	52.7	16	0.002	2.0	B,3			
10/01/1999	75.2	52.7	17	0.002	1.0	C,3			
10/01/1999	75.2	52.7	4	0.002	4.0	D,14-13			
10/01/1999	75.2	52.7	6	0.002	6.0	D,4			
10/01/1999	75.2	52.7	6	0.002	3.0	D,1			
10/01/1999	75.2	52.7	8	0.002	54.0	F,15-11			

Table 3. Continued...

Date	Temp	Relative Humidity	Crack No	No Load on Bridge			Truck Load on Bridge		
				Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
	(°F)	(%)							
10/01/1999	75.2	52.7	10	0.002	2.5	F,1			
10/01/1999	75.2	52.7	18	0.002	11.0	G,11-10			
10/01/1999	75.2	52.7	19	0.002	29.0	G,9-7	0.002	29.0	G,9-7
10/01/1999	75.2	52.7	20	0.002	17.0	G,7-6	0.002	17.0	G,7-6
10/01/1999	75.2	52.7	21	0.002	2.0	G,4			
10/01/1999	75.2	52.7	22	0.002	1.0	G,1			
10/01/1999	75.2	52.7	13	0.003	2.5	H,2			
10/01/1999	75.2	52.7	14	0.002	54.0	I,14-12			
10/01/1999	75.2	52.7	23	0.003	26.0	I,5-4	0.003	26.0	I,5-4
10/01/1999	75.2	52.7	24	0.002	3.0	I,2			
11/08/1999	68	18.3	25	0.002	22.0	C,7-5			
11/08/1999	68	18.3	26	0.002	2.0	C,4			
11/08/1999	68	18.3	17	0.002	3.0	C,3			
11/08/1999	68	18.3	27	0.002	1.0	C,3			
11/08/1999	68	18.3	28	0.002	5.0	F,6			
11/08/1999	68	18.3	18	0.002	4.0	G,13			
11/08/1999	68	18.3	20	0.002	7.0	G,7-6			
11/08/1999	68	18.3	12	0.002	3.5	H,7			
11/08/1999	68	18.3	13	0.002	4.0	H,2			
11/08/1999	68	18.3	14	0.002	3.0	I,12			
11/08/1999	68	18.3	24	0.002	7.0	I,2			
12/09/1999	62.8	44.5	8	0.002	8.0	F,14	0.002	4.0	F,14
12/09/1999	62.8	44.5	12	0.002	1.0	H,5	0.002	1.0	H,5
12/09/1999	62.8	44.5	23	0.002	24.0	I,5-3	0.002	24.0	I,5-3
02/25/2000	65.5	58	6	0.002	8.0	D,4			

Table 3. Continued...

Date	Temp	Relative Humidity	Crack No	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)		Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
02/25/2000	65.5	58	8	0.002	1.0	F,14			
02/25/2000	65.5	58	19	0.003	3.0	G,8			
02/25/2000	65.5	58	14	0.002	2.0	I,11			
02/25/2000	65.5	58	12	0.002	3.0	H,4			
03/17/2000	38.3	42	25	0.002	14.0	C,6-5	0.002	14.0	C,6-5
03/17/2000	38.3	42	5	0.002	4.5	D,7	0.002	4.5	D,7-6
03/17/2000	38.3	42	8	0.002	21.0	F,11-10	0.002	21.0	F,11-10
03/17/2000	38.3	42	10	0.002	6.0	F,1	0.002	6.0	F,1
03/17/2000	38.3	42	11	0.002	9.5	G,15	0.002	9.5	G,15
03/17/2000	38.3	42	18	0.002	38.0	G,13-10	0.002	38.0	G,13-10
03/17/2000	38.3	42	19	0.002	28.0	G,9-7	0.002	28.0	G,9-7
03/17/2000	38.3	42	24	0.002	15.0	I,2	0.002	15.0	I,2
07/10/2000	100.8	42.2	26	0.002	6.0	C,15			
07/10/2000	100.8	42.2	25	0.002	6.0	C,6			
07/10/2000	100.8	42.2	25	0.002	18.0	C,5-4			
07/10/2000	100.8	42.2	5	0.003	8.0	D,9			
07/10/2000	100.8	42.2	5	0.002	22.0	D,8-7			
07/10/2000	100.8	42.2	6	0.002	8.0	D,5			
07/10/2000	100.8	42.2	18	0.003	3.0	G,14			
07/10/2000	100.8	42.2	18	0.003	22.0	G,13-11			
07/10/2000	100.8	42.2	19	0.003	29.0	G,9			
07/10/2000	100.8	42.2	19	0.002	9.0	G,9-7			
07/10/2000	100.8	42.2	20	0.002	9.0	G,7-6			
07/10/2000	100.8	42.2	21	0.002	7.0	G,4			
07/10/2000	100.8	42.2	10	0.002	16.0	F,1			

Table 3. Continued...

Date	Temp (^{0}F)	Relative Humidity (%)	Crack No	No Load on Bridge			Truck Load on Bridge		
				Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
07/10/2000	100.8	42.2	12	0.002	16.0	H,7-6			
07/10/2000	100.8	42.2	13	0.002	8.0	H,2			
07/10/2000	100.8	42.2	14	0.003	4.0	I,10			
07/10/2000	100.8	42.2	24	0.002	8.0	I,2			

Table 4. Details of Crack No. 1 Observed in the Top Surface of the Bridge Deck from 6/19/98 to 10/1/99 Within GFRP Reinforced Area With no Load on Bridge

Date	Temp (^{0}F)	Relative Humidity (%)	Crack Width (in)	Crack Length (in)	Grid Location
06/19/1998	91	75	0.003	2.5	I,8-10
06/26/1998	95	100	0.002	2.5	I,8-9
08/11/1998	70	100	0.002	2	I,8-9
05/28/1999	75.2	36	0.002	2.5	I,8
05/28/1999	75.2	36	0.009	1	I,10
06/25/1999	79.9	59	0.002	4	I,9-10
07/21/1999	74.3	88.8	0.002	33	I,6-8
10/01/1999	75.2	52	0.003	2.5	I,8-9

Table 5. Details of Crack No. 2 Observed in the Top Surface of the Bridge Deck from 6/26/98 to 6/25/99 Within GFRP Reinforced Area With no Load on Bridge

Date	Temp (^{0}F)	Relative Humidity (%)	Crack Width (in)	Crack Length (in)	Grid Location
06/26/1998	95	100	0.001	2.3	I,15
08/11/1998	70	100	0.003	1	I,15
09/08/1998	70	40	0.003	1	I,15
10/16/1998	57	80	0.002	1.5	I,15
05/28/1999	75.2	36	0.003	1.5	I,15
06/25/1999	79.9	59	0.002	2.5	I,15

Table 6. Details of Crack No. 11 Observed in the Top Surface of the Bridge Deck from 12/18/98 to 3/17/2000 Within GFRP Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack width (in)	Crack Length (in)	Grid Location
12/18/1998	45	40	0.003	120	E,1-10			
03/05/1999	38	45	0.002	120	E,1-10			
04/16/1999	40	50	0.003	120	E,1-10	0.001	120	E,1-12
05/28/1999	75.2	36	0.005	120	E,1-10			
06/25/1999	79.9	59	0.005	102	E,1-9			
07/21/1999	74.3	88.8	0.003	163	E,1-15			
08/23/1999	94.6	36.9	0.003	115	E,1-12			
10/01/1999	75.2	52	0.007	116	E,1-12	0.009	116	E,1-12
11/18/1999	68	18.3	0.005	106	E,1-10			
12/09/1999	62.8	44.5	0.005	112	E,1-10	0.013	112	E,1-10
02/25/2000	65.5	58	0.003	106	E,1-10			
03/17/2000	38.3	42	0.005	120	E,1-10	0.013	120	E,1-12

Table 7. Details of Crack No. 12 Observed in the Top Surface of the Bridge Deck from 4/16/99 to 11/18/99 Within GFRP Reinforced Area With no Load on Bridge

Date	Temp (^{0}F)	Relative Humidity (%)	Crack Width (in)	Crack Length (in)	Grid Location
04/16/1999	40	50	0.002	1.5	H,14-15
05/28/1999	75.2	36	0.002	5	H,14-15
06/25/1999	79.9	59	0.002	1.8	H,14
08/23/1999	94.6	36.9	0.002	6	H,12-13
10/01/1999	75.2	52	0.002	4	H,12
11/18/1999	68	18.3	0.002	9	H,14

Table 8. Details of Crack No. 1 Observed in the Bottom Surface of the Bridge Deck from 6/19/98 to 7/10/2000 Within GFRP Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
06/19/1998	91	75	0.007	64	E,3-8			
06/26/1998	95	100	0.005	64	E,3-8	0.007	64	E,3-8
08/11/1998	70	100	0.005	64	E,3-8	0.007	64	E,3-8
09/08/1998	70	40	0.005	64	E,3-8			
12/18/1998	45	40	0.005	76.5	E,3-8			
04/16/1999	40	50	0.003	64	E,3-8	0.007	64	E,3-8
05/28/1999	75.2	36	0.002	64	E,3-8			
06/25/1999	79.9	59	0.005	102	E,3-9			
07/21/1999	74.3	88.8	0.005	104	E,3-9	0.005	104	E,3-8
08/23/1999	94.6	36.9	0.002	94.4	E,3-8			
10/01/1999	75.2	52	0.003	192	E,1-16	0.003	192	E,1-16
11/18/1999	68	18.3	0.002	192	E,1-16			
12/09/1999	62.8	44.5	0.002	192	E,1-16	0.005	192	E,1-16
07/10/2000	100.7	42.22	0.003	120	E,1-10			

Table 9. Details of Crack No. 5 Observed in the Top Surface of the Bridge Deck from 8/23/99 to 7/10/2000 Within Steel Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
08/23/1999	94.6	36.9	0.002	33	D,9-7			
03/17/2000	38.3	42	0.002	4.5	D,7	0.002	4.5	D,7-5
07/10/2000	100.8	42.2	0.003	8	D,9-7			
07/10/2000	100.8	42.2	0.002	22	D,8-7			

Table 10. Details of Crack No. 6 Observed in the Top Surface of the Bridge Deck from 8/23/99 to 7/10/2000 Within Steel Reinforced Area With no Load on Bridge

Date	Temp (^{0}F)	Relative Humidity (%)	Crack Width (in)	Crack Length (in)	Grid Location
08/23/1999	94.6	36.9	0.003	54	D,5-1
10/01/1999	75.2	52.7	0.002	6	D,4
02/25/2000	65.5	58	0.002	8	D,4
07/10/2000	100.8	42.2	0.002	8	D,5

Table 11. Details of Crack No. 8 Observed in the Top Surface of the Bridge Deck from 8/1/99 to 3/17/2000 Within Steel Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
08/01/1999	24	52.7	0.002	54	F,15-11			
08/23/1999	94.6	36.9	0.002	16	F,12-11			
12/09/1999	62.8	44.5	0.002	8	F,14	0.002	4	F,14
02/25/2000	65.5	58	0.002	1	F,14			
03/17/2000	38.3	42	0.002	21	F,11-10	0.002	21	F,11-10

Table 12. Details of Crack No. 10 Observed in the Top Surface of the Bridge Deck from 8/23/99 7/10/2000 Within Steel Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
08/23/1999	94.6	36.9	0.005	8	F,1			
10/01/1999	75.2	52.7	0.002	2.5	F,1			
03/17/2000	65.5	42	0.002	6	F,1	0.002	6	F,1
07/10/2000	100.8	42.2	0.002	16	F,1			

Table 13. Details of Crack No. 12 Observed in the Top Surface of the Bridge Deck from 8/23/99 to 7/10/2000 Within Steel Reinforced Area

Date	Temp (^{0}F)	Relative Humidity (%)	No Truck on Bridge			Truck Load on Bridge		
			Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
08/23/1999	94.6	36.9	0.002	32	H,7-4			
11/08/1999	68	18.3	0.002	3.5	H,7-4			
12/09/1999	62.8	44.5	0.002	1	H,5	0.002	1	H,5
02/25/2000	65.5	58	0.002	3	H,4			
07/10/2000	100.8	42.2	0.002	16	H,7-6			

Table 14. Details of Crack No. 13 Observed in the Top Surface of the Bridge Deck from 8/23/99 to 7/10/2000 Within Steel Reinforced Area With no Load on Bridge

Date	Temp (^{0}F)	Relative Humidity (%)	Crack Width (in)	Crack Length (in)	Grid Location
08/23/1999	94.6	36.9	0.003	82.5	H,7-1
10/01/1999	75.2	52.7	0.003	2.5	H,2
11/08/1999	68	18.3	0.002	4	H,2
07/10/2000	100.8	42.2	0.002	8	H,2

Table 15. Details of Crack No. 14 Observed in the Top Surface of the Bridge Deck from 8/23/99 to 7/10/2000 Within Steel Reinforced Area With no Load on Bridge

Date	Temp (^{0}F)	Relative Humidity (%)	Crack Width (in)	Crack Length (in)	Grid Location
08/23/1999	94.6	36.9	0.002	20	I,12-9
10/01/1999	75.2	52.7	0.002	54	I,14-12
11/08/1999	68	18.3	0.002	2	I,12
02/25/2000	65.5	58	0.002	2	I,11
07/10/2000	100.8	42.2	0.003	4	I,10

Table 16. Details of Crack No. 18 Observed in the Top Surface of the Bridge Deck from 10/1/99 to 7/10/2000 Within Steel Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
10/01/1999	75.2	52.7	0.002	11	G,11-10			
11/08/1999	68	18.3	0.002	4	G,13			
03/17/2000	38.3	42	0.002	38	G,13-10	0.002	38	G,13-10
07/10/2000	100.8	42.2	0.003	3	G,14			
07/10/2000	100.8	42.2	0.003	22	G,13-11			

Table 17. Details of Crack No. 19 Observed in the Top Surface of the Bridge Deck from 10/1/99 to 7/10/2000 Within Steel Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
10/01/1999	75.2	52.7	0.002	29	G,9-7	0.002	29	G,9-7
02/25/2000	65.5	58	0.003	3	G,8			
03/17/2000	38.3	42	0.002	28	G,9-7	0.002	28	G,9-7
07/10/2000	100.8	42.2	0.003	29	G,9			
07/10/2000	100.8	42.2	0.002	9	G,9-7			

Table 18. Details of Crack No. 24 Observed on the Top Surface of the Bridge Deck from 10/1/99 7/10/2000 for Steel Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
10/01/1999	75.2	52.7	0.002	3	I,2			
11/08/1999	68	18.3	0.002	7	I,2			
03/17/2000	38.3	42	0.002	15	I,2	0.002	15	I,2
07/10/2000	100.8	42.2	0.002	8	I,2			

Table 19. Details of Crack No. 25 Observed in the Top Surface of the Bridge Deck from 11/8/99 to 7/10/2000 Within Steel Reinforced Area

Date	Temp	Relative Humidity	No Load on Bridge			Truck Load on Bridge		
	(^{0}F)	(%)	Crack Width (in)	Crack Length (in)	Grid Location	Crack Width (in)	Crack Length (in)	Grid Location
11/08/1999	68	18.3	0.002	22	C,7-5			
03/17/2000	38.3	42	0.002	14	C,6-5	0.002	14	C,6-5
07/10/2000	100.8	42.2	0.002	6	C,6			
07/10/2000	100.8	42.2	0.002	18	C,5-4			

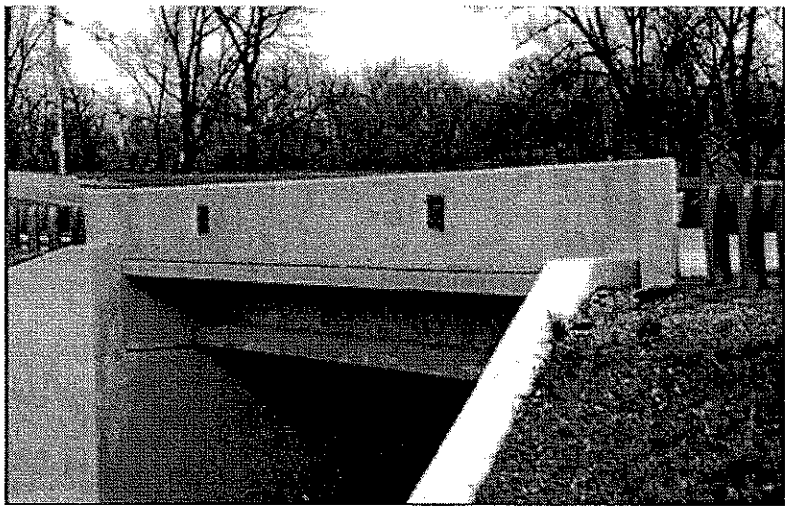


Figure 4.1. Rogers' Creek Bridge - Bourbon County

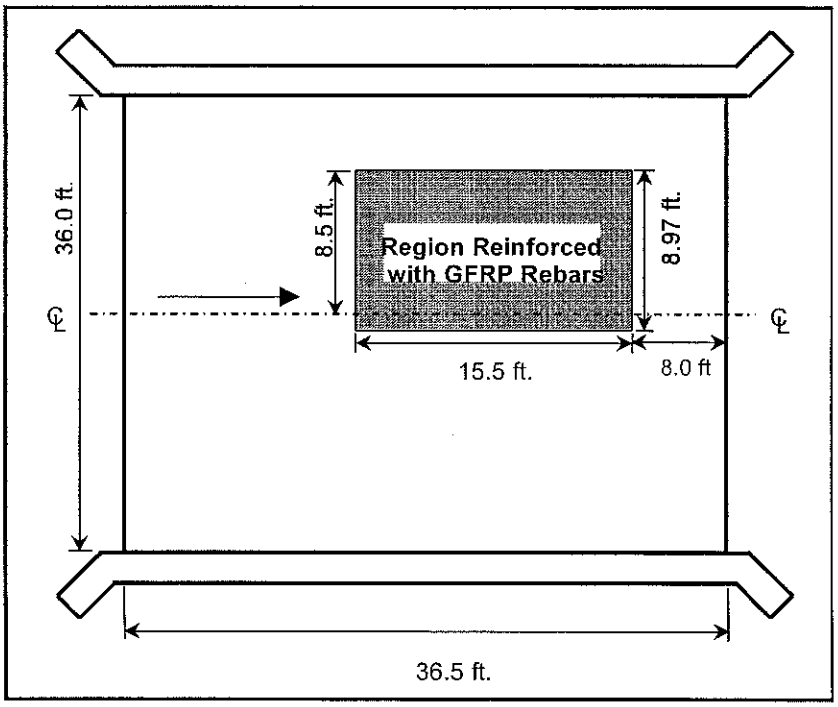


Figure 4.2. Plan View of Bridge Deck Showing the Location of the GFRP Rebars

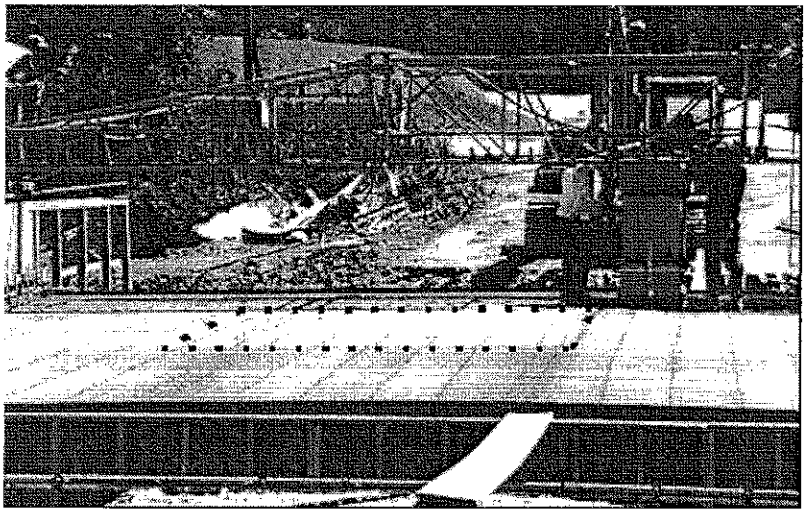


Figure 4.3. Photograph of Bridge Deck Prior to Concrete Placement. Dots were sketched to identify the location of GFRP Reinforcement

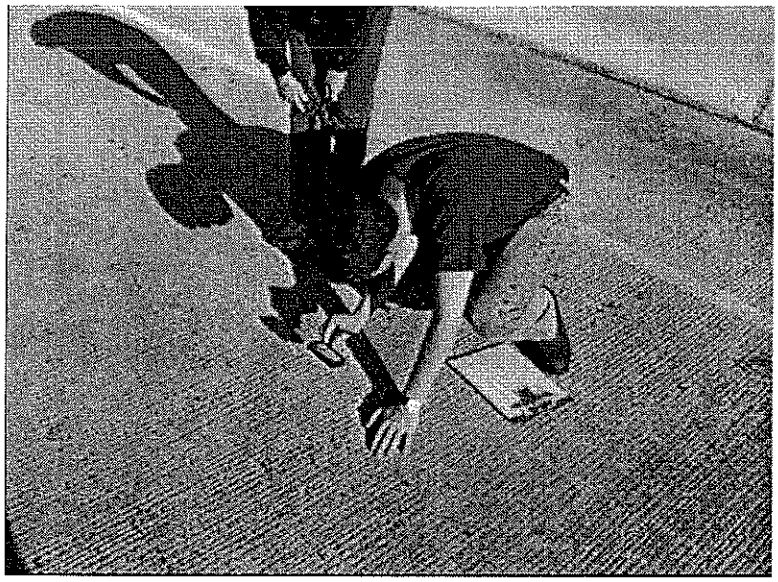


Figure 5.1. Visual Inspection of Cracks Using a Magnifying Glass

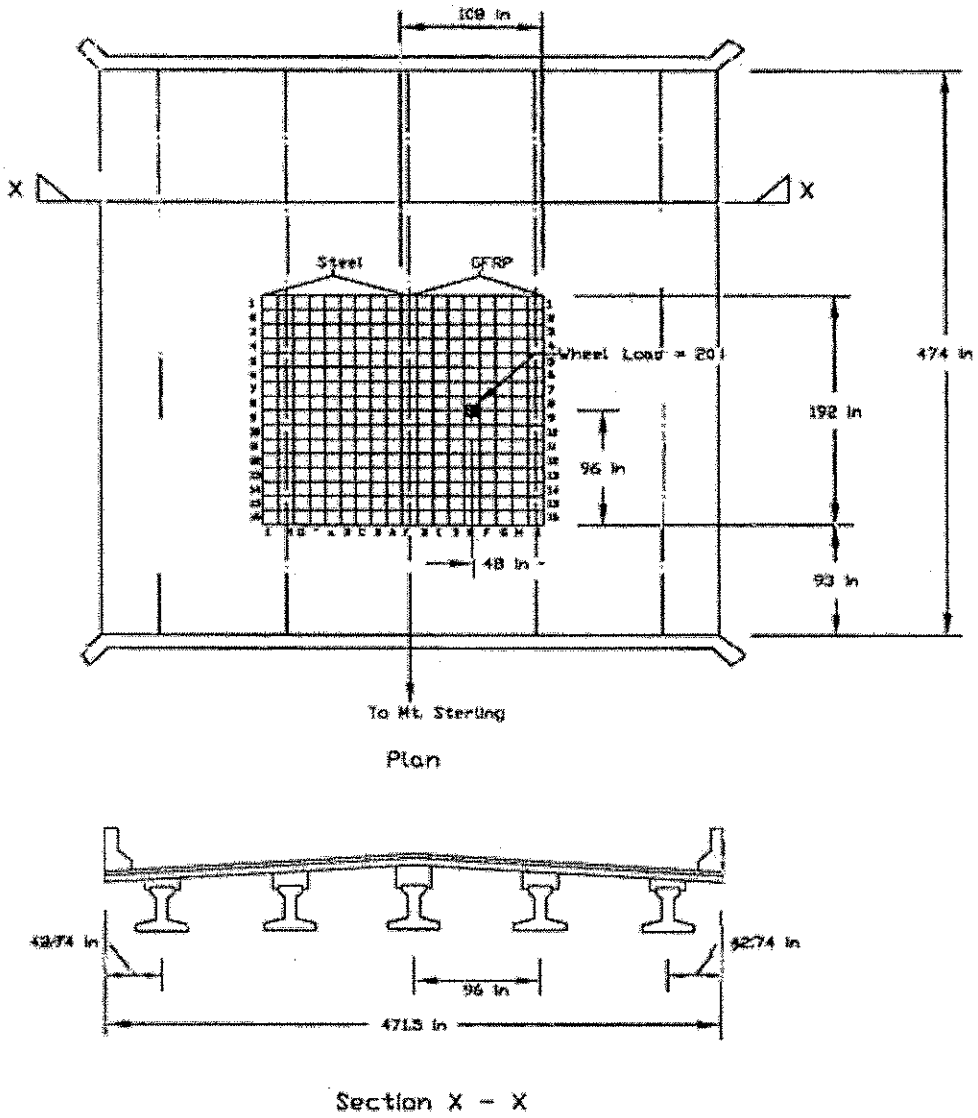


Figure 5.2. Location of GFRP Reinforced Grids on the Bridge

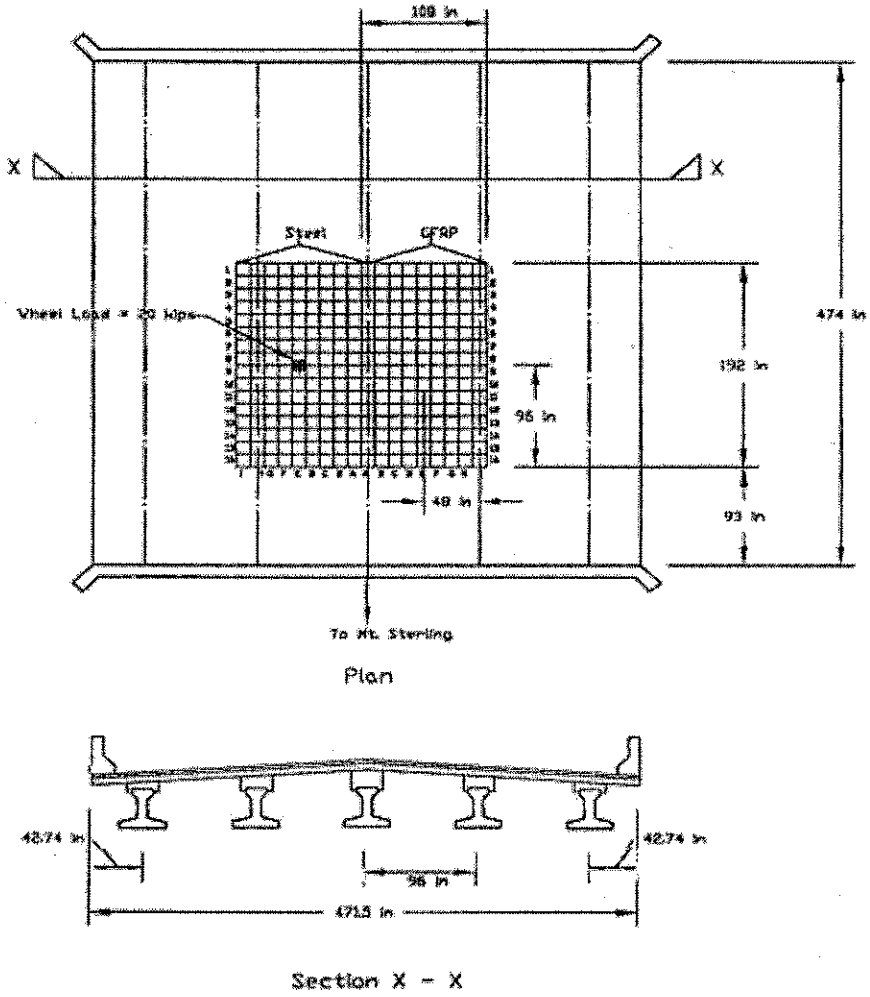


Figure 5.3. Location of Steel Reinforced Grids on the Bridge

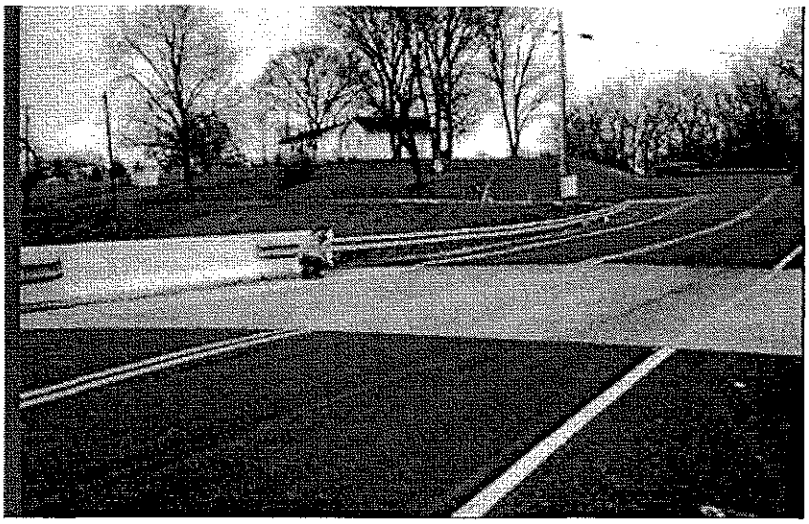


Figure 6.1. Measurement of Cracks With no Load on Bridge

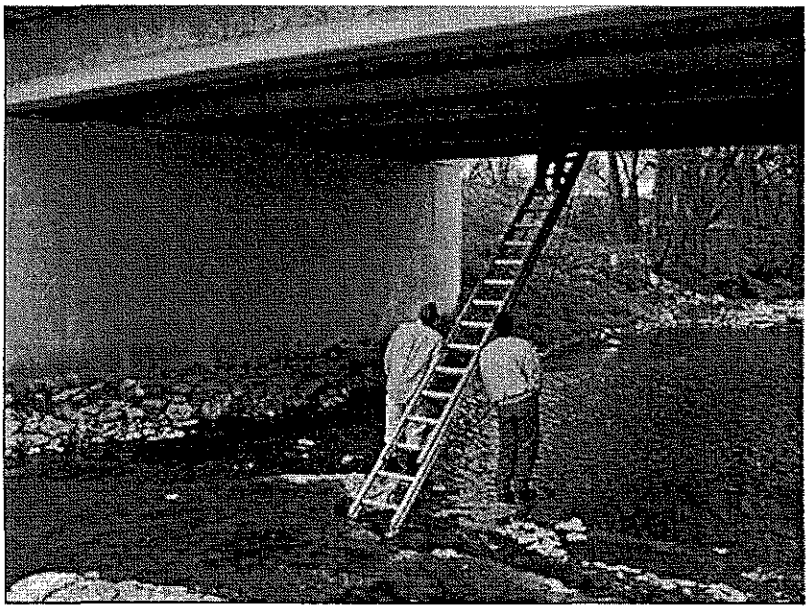
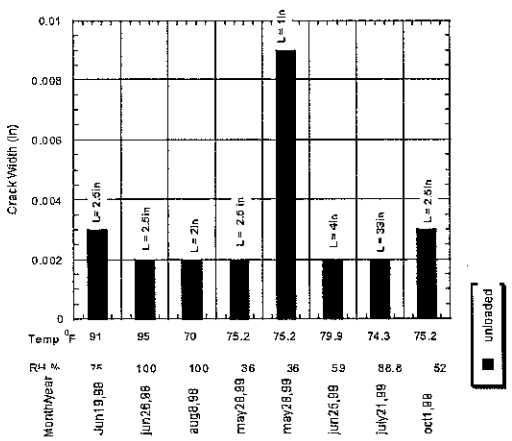
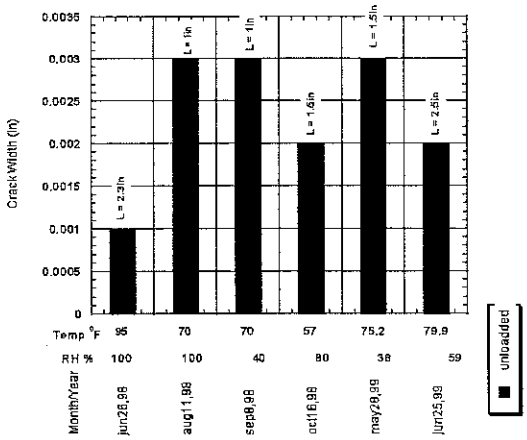


Figure 6.2. Inspection of Cracks at the Bottom Surface of the Bridge Deck

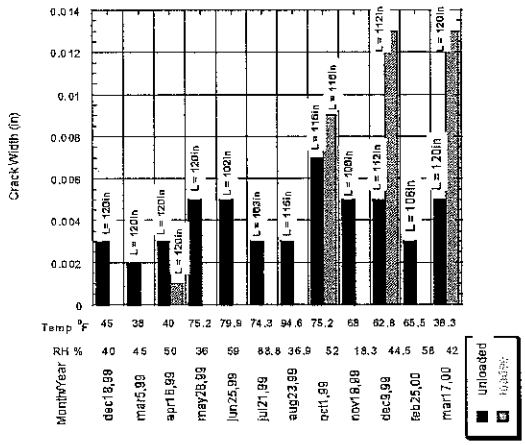
Figure 6.3. Photograph Showing the Truck Load on the Bridge Deck



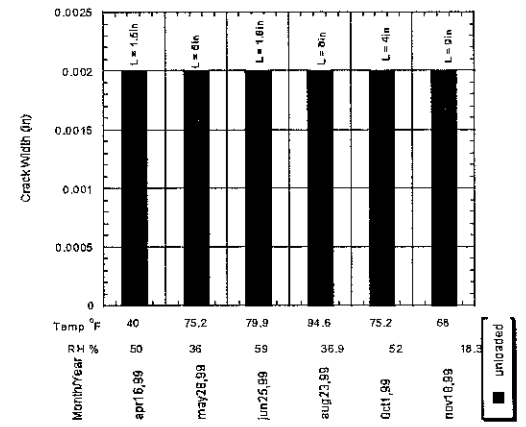
(a) Crack No. 1



(b) Crack No. 2



(c) Crack No. 11



(d) Crack No. 12

Figures 7.1. (a) to (d); Graphical Variation of Cracks Observed in the Top Surface of the Bridge Deck in GFRP Reinforced Area

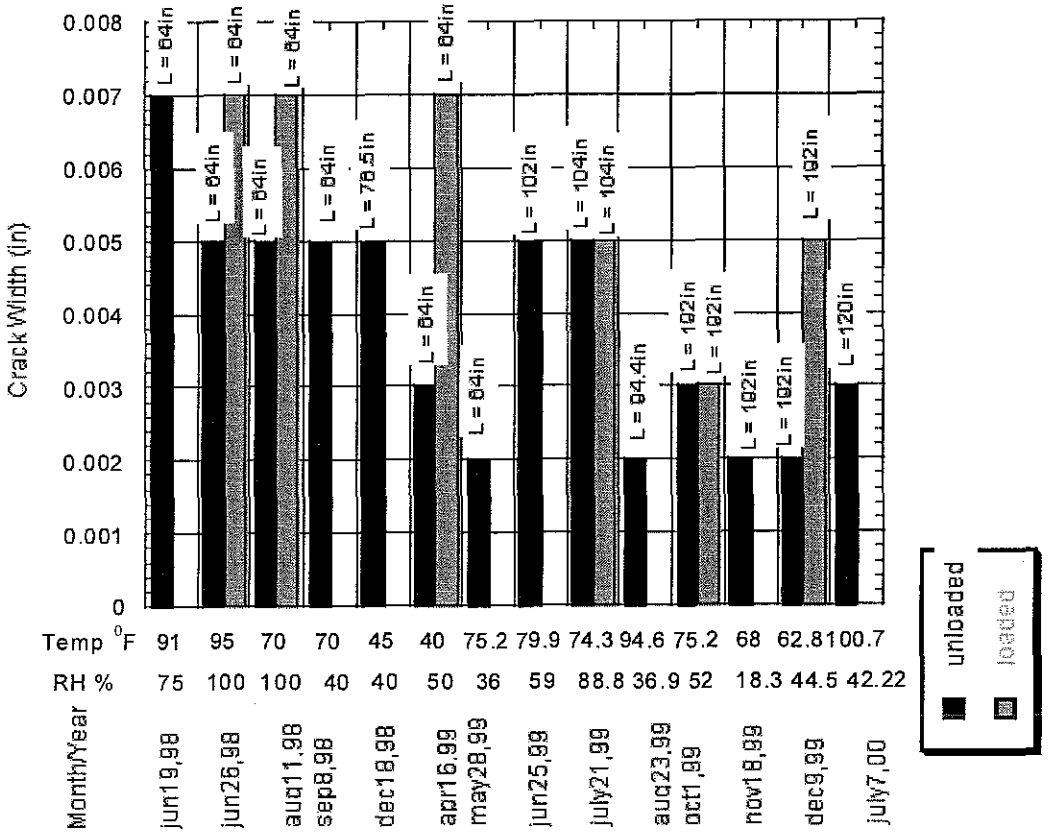
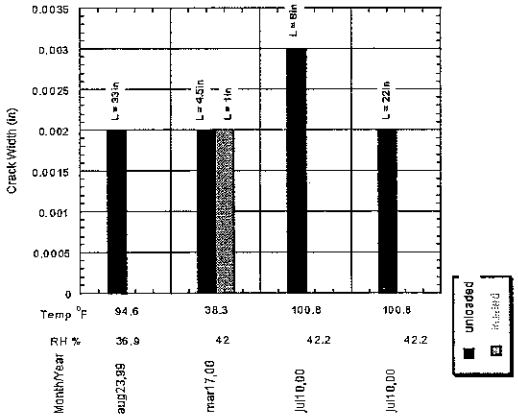
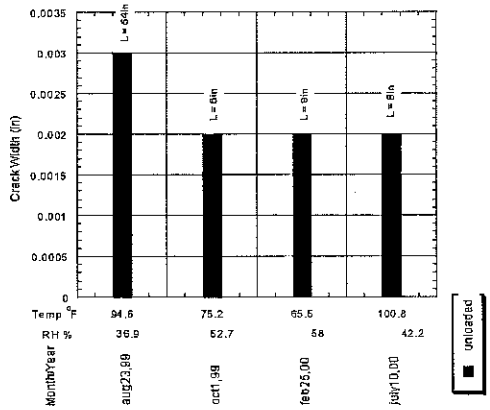


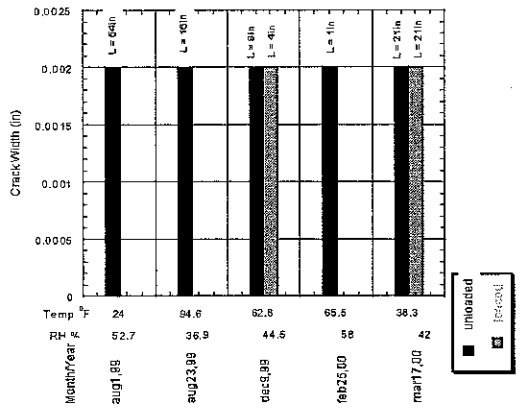
Figure 7.2. Graphical Variation of Crack No. 1 Observed in the Bottom Surface of the Bridge Deck in GFRP Reinforced Area



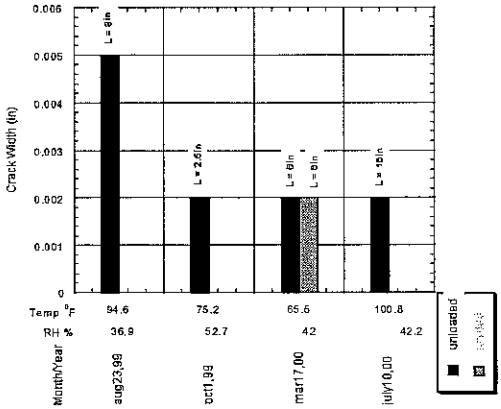
(a) Crack No. 5



(b) Crack No. 6

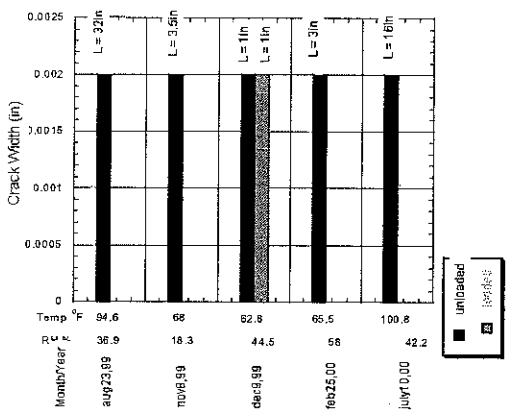


(c) Crack No. 8

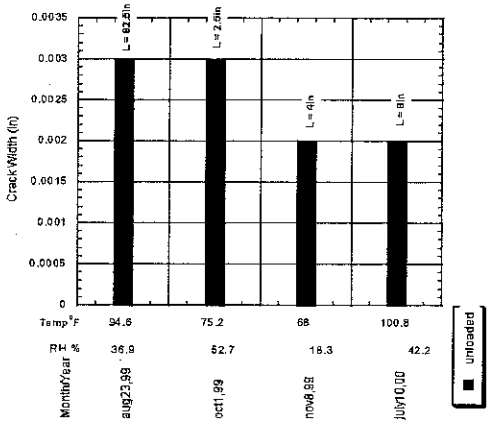


(d) Crack No. 10

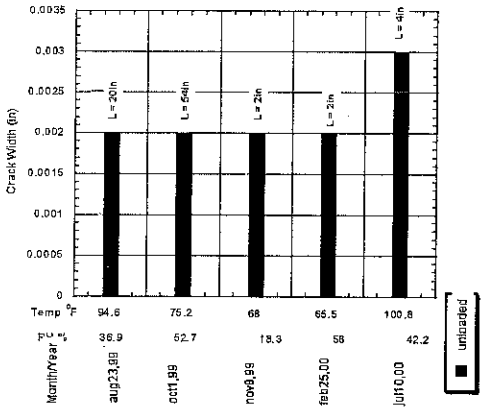
Figure 7.3. (a) to (d); Graphical Variation of Cracks Observed in the Top Surface of the Bridge Deck in Steel Reinforced Area



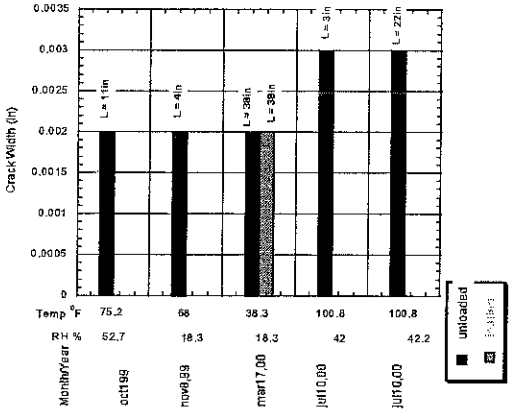
(a) Crack No. 12



(b) Crack No. 13

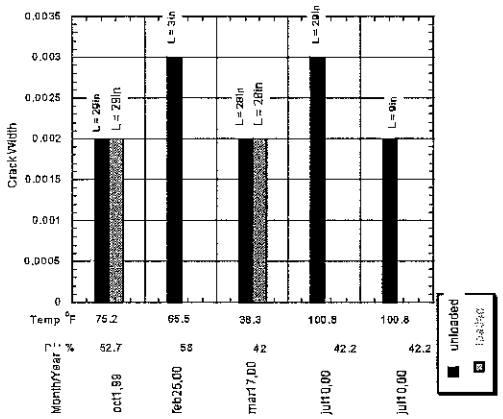


(c) Crack No. 14

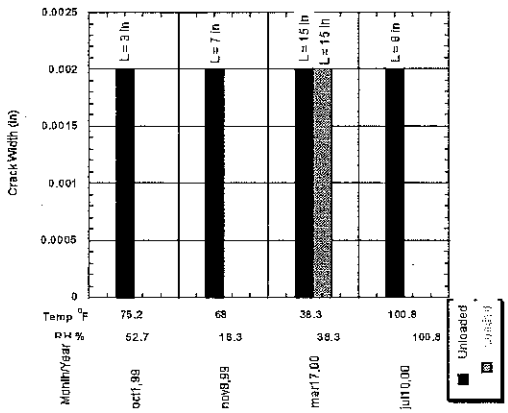


(d) Crack No. 18

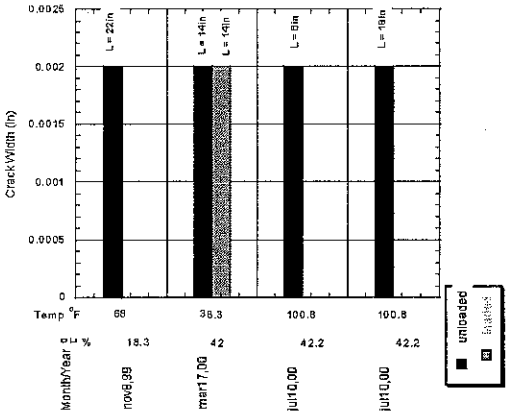
Figure 7.4. (a) to (d); Graphical Variation of Cracks Observed in the Top Surface of the Bridge Deck in Steel Reinforced Area



(a) Crack No. 19



(b) Crack No. 24



(c) Crack No. 25

Figure 7.5. (a) to (c); Graphical Variation of Cracks Observed in the Top Surface of the Bridge Deck in Steel Reinforced Area

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Appendix A

Cracks Observed in the CFRP Reinforced Area

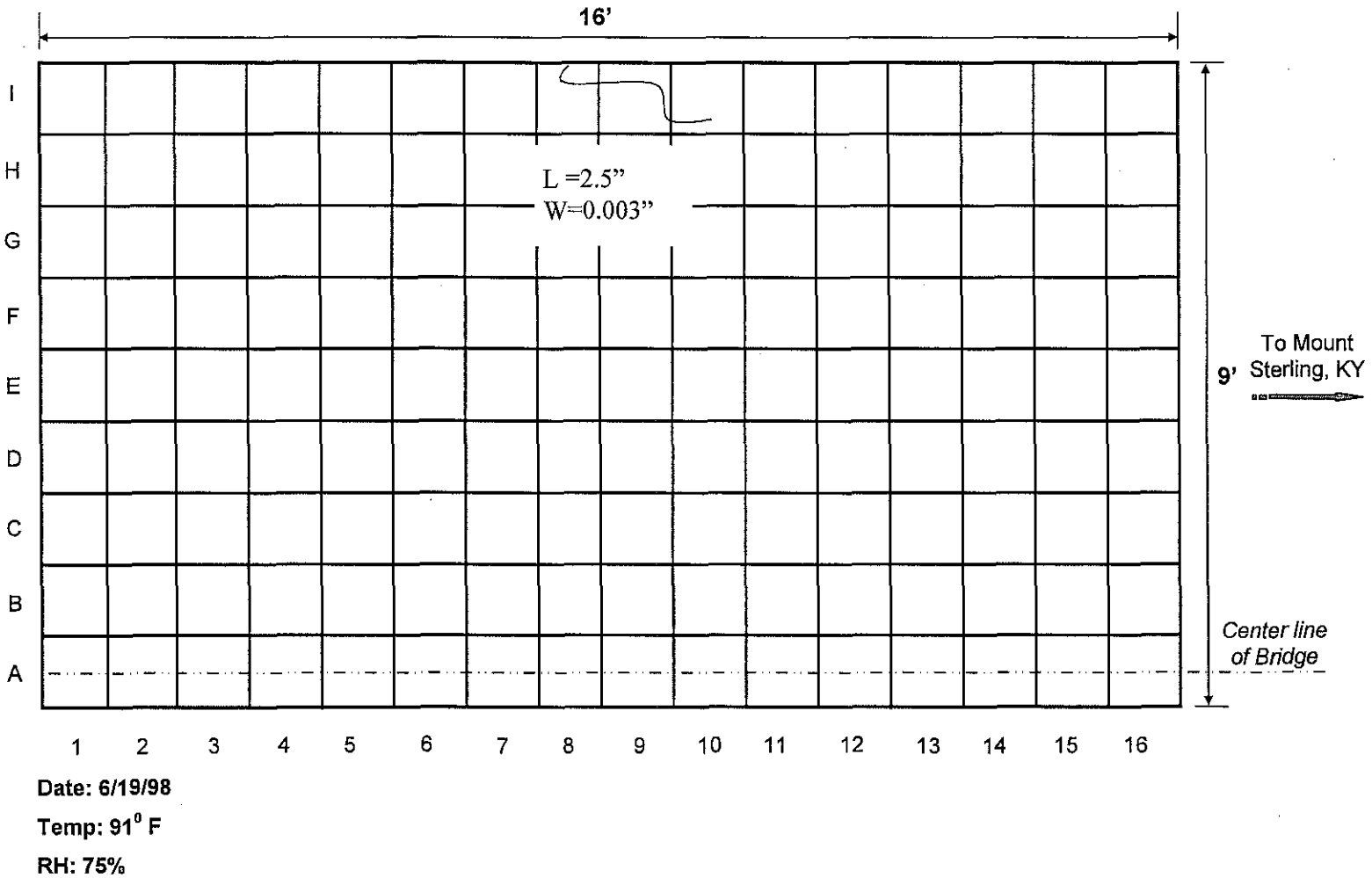


Fig. A1. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

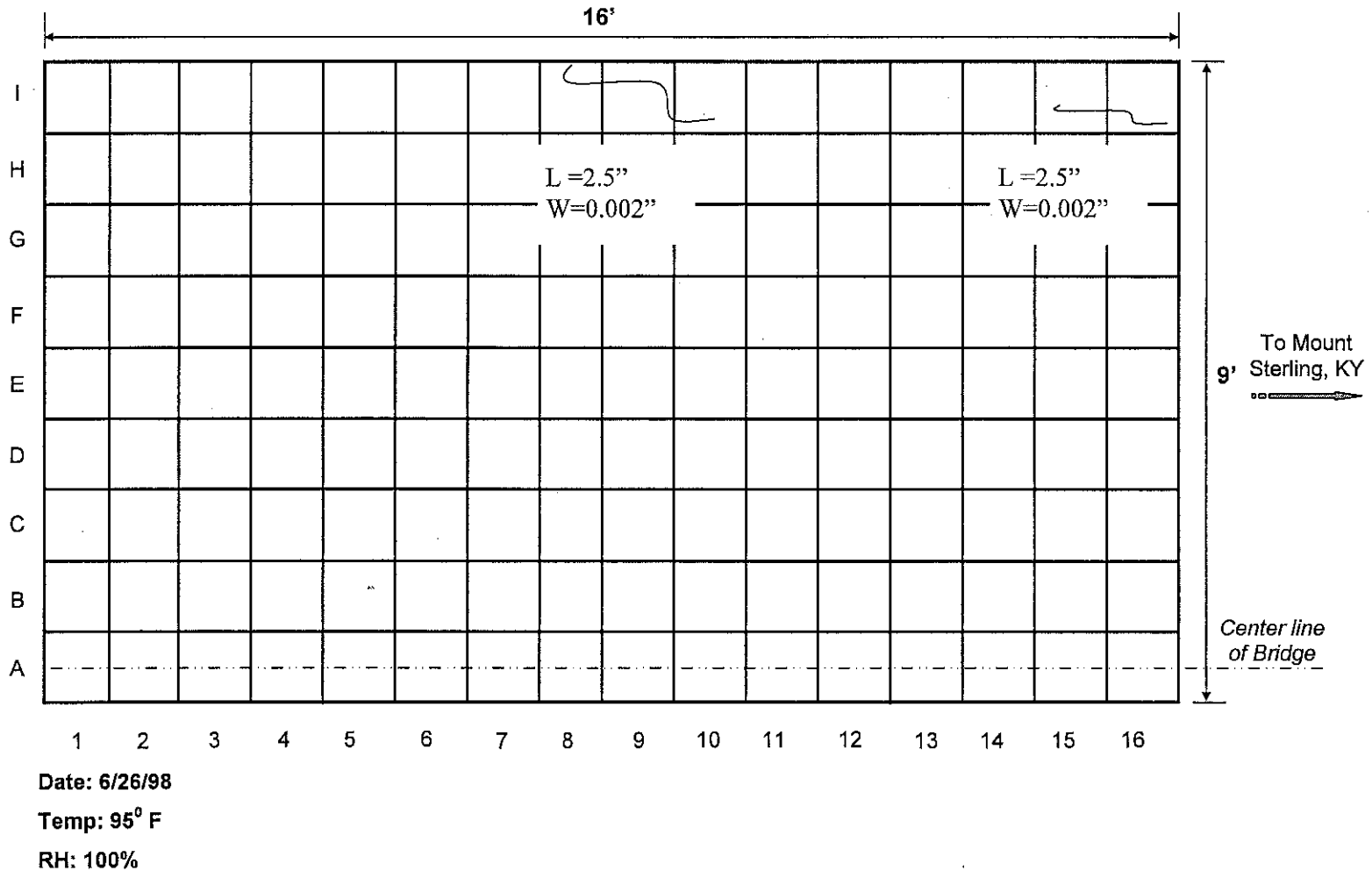


Fig. A2. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

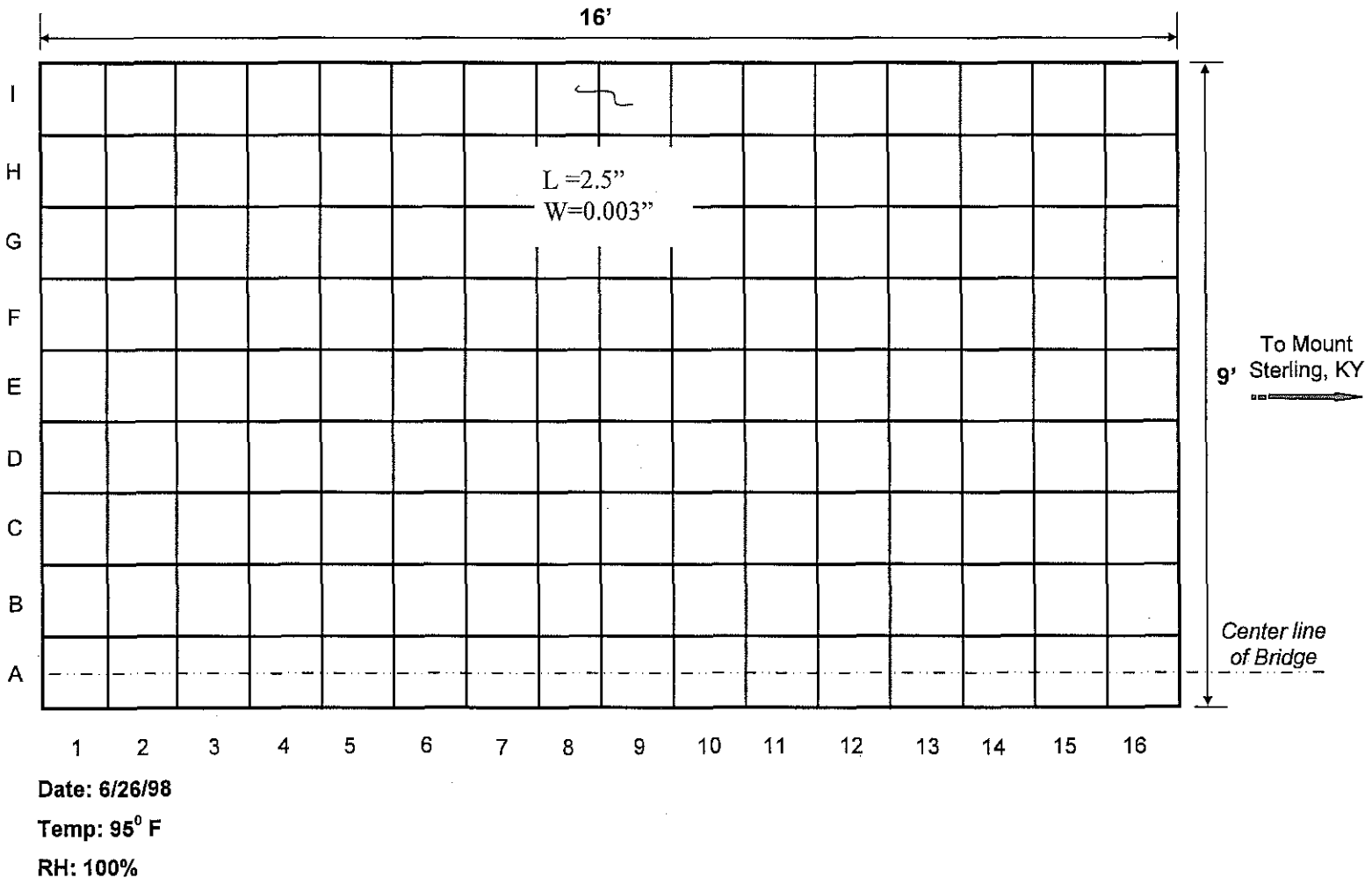


Fig. A3. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

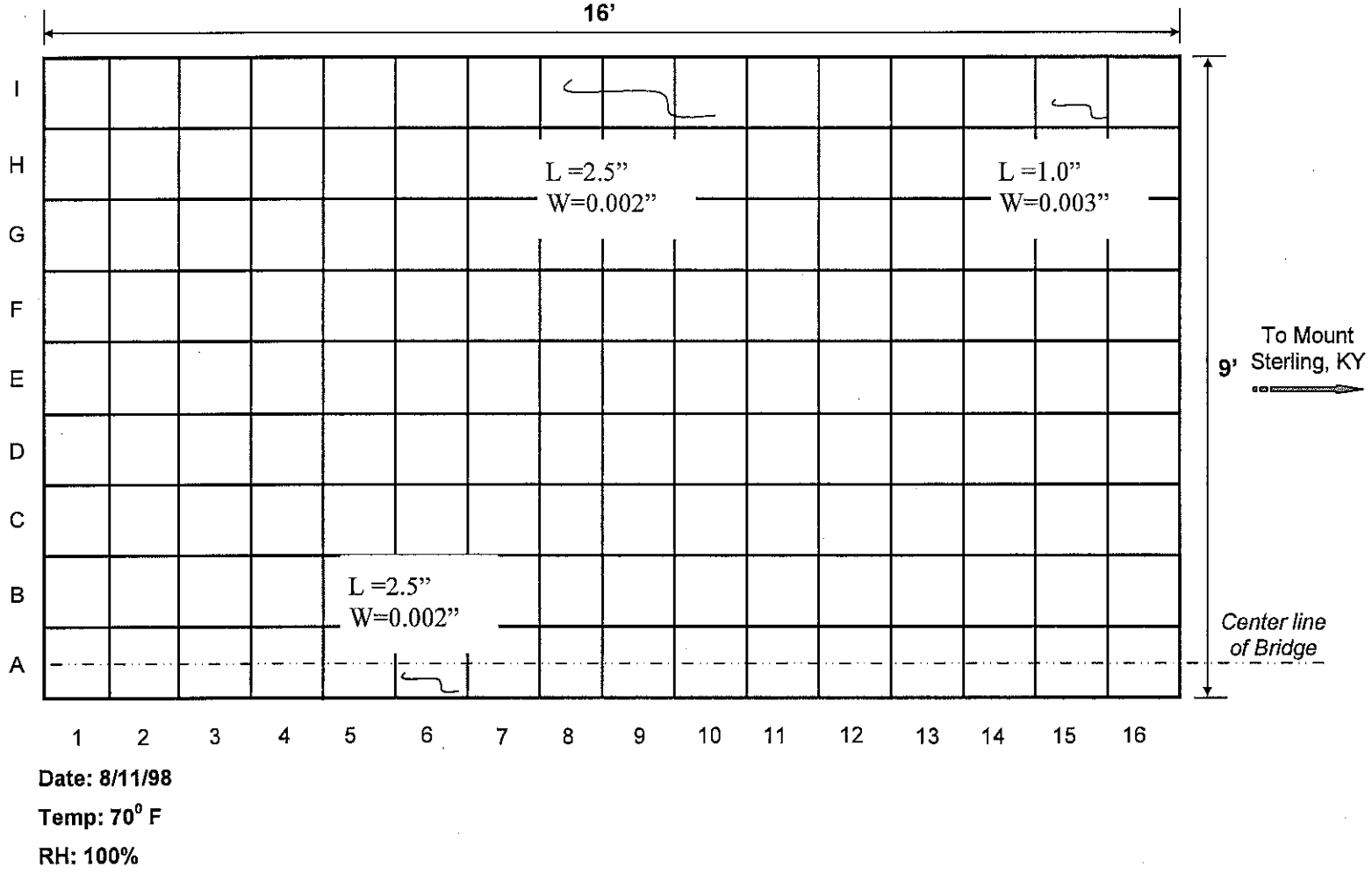


Fig. A4. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

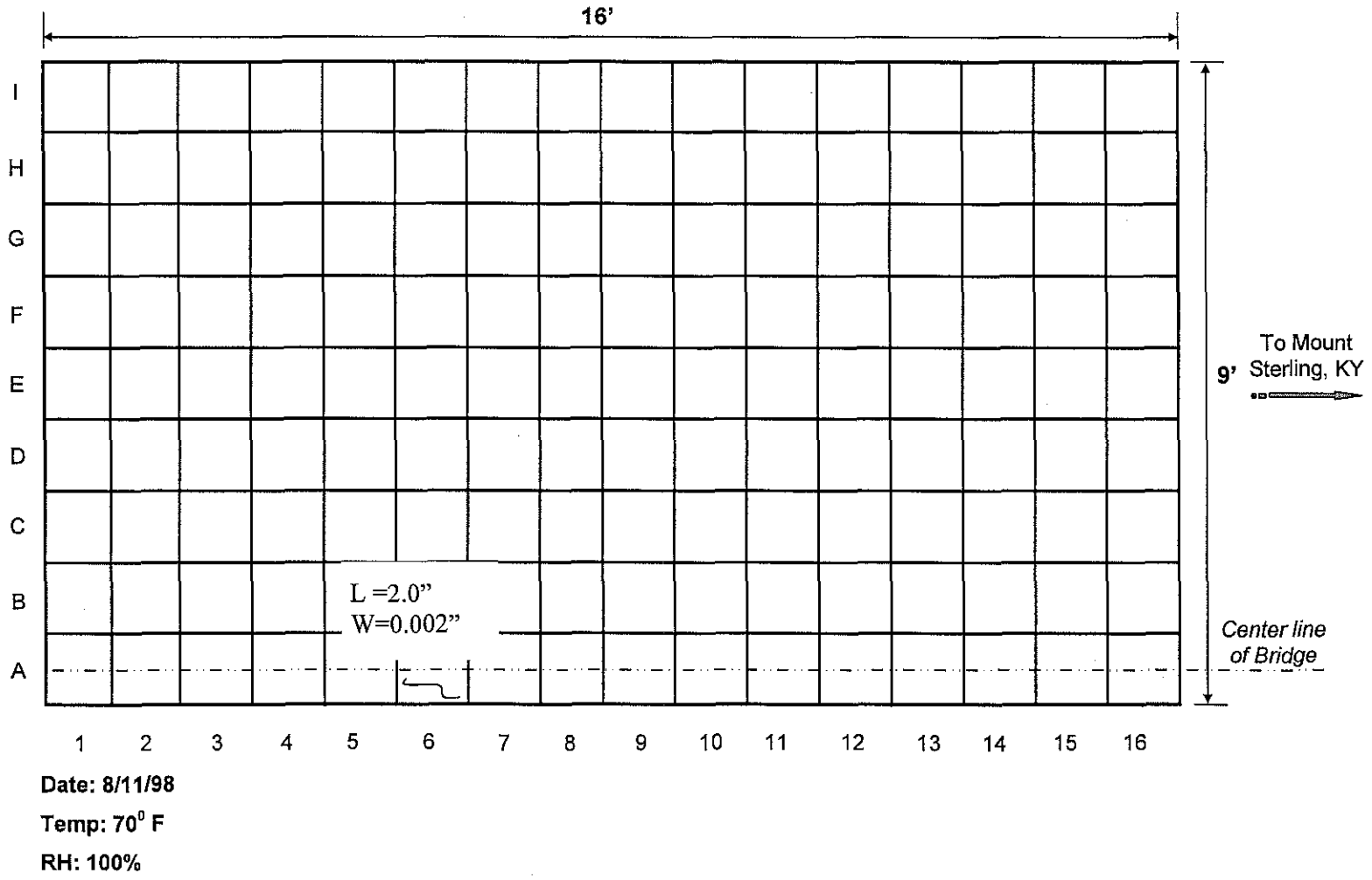


Fig. A5. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

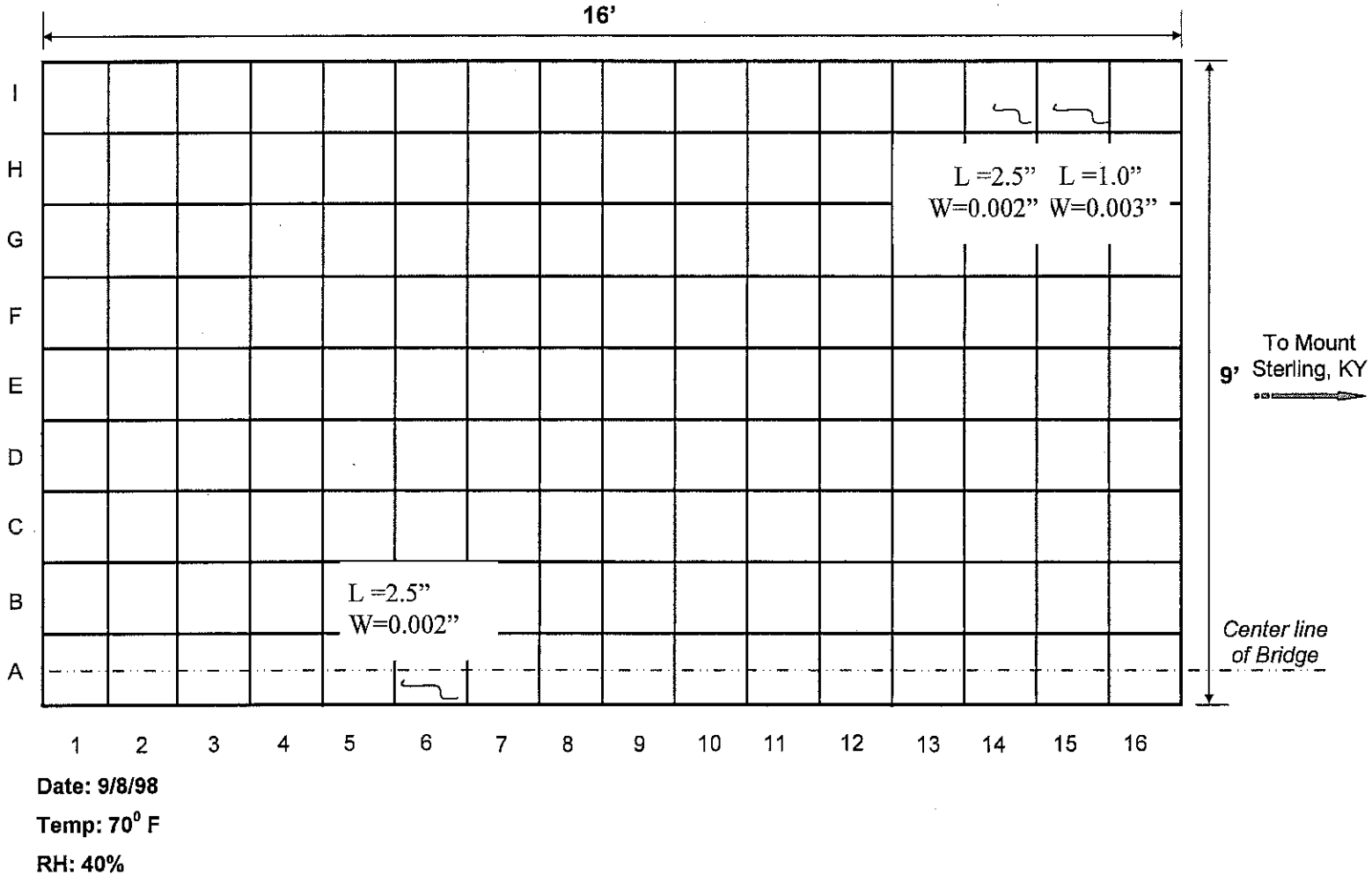


Fig. A6. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

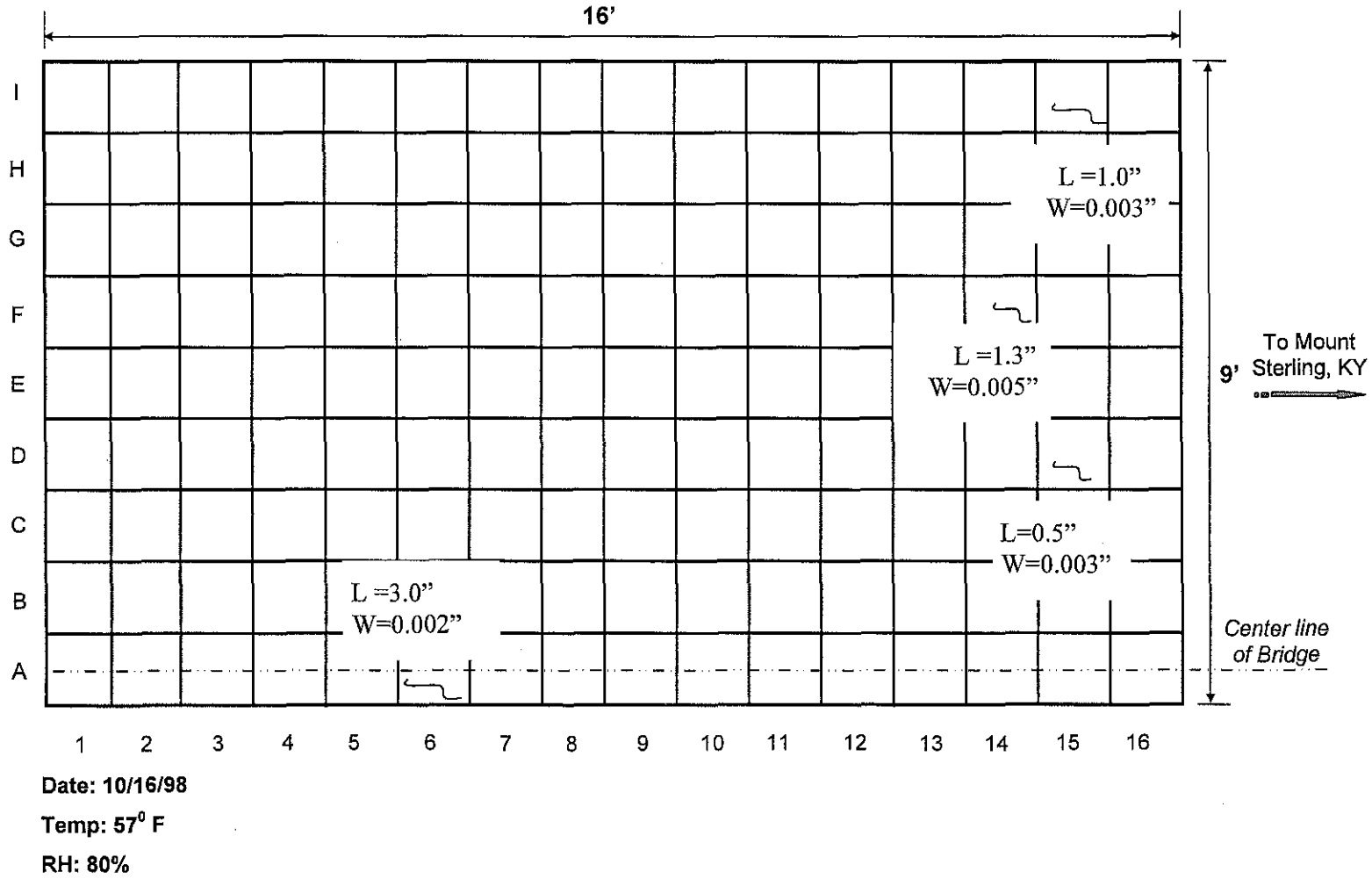


Fig. A7. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

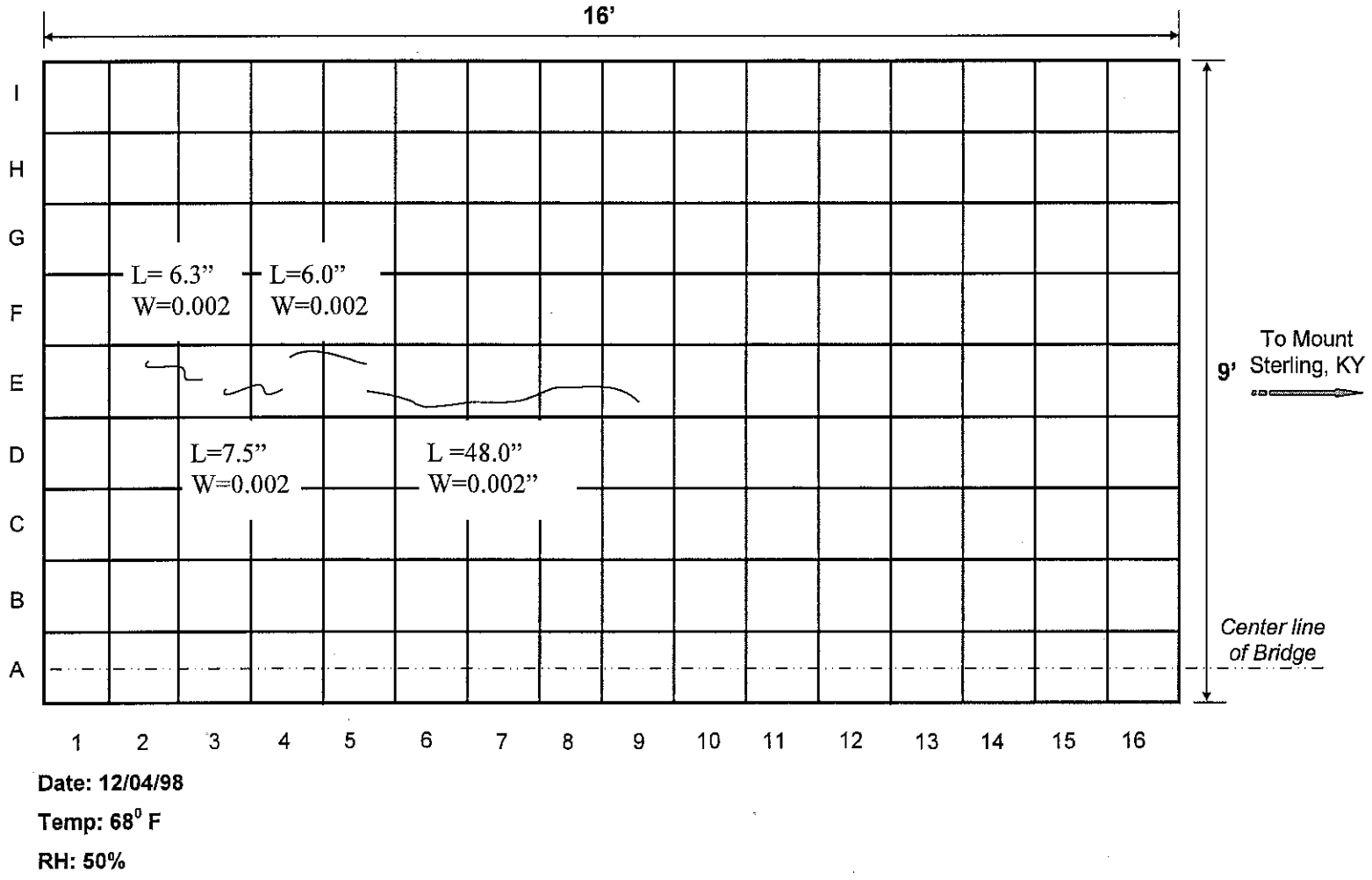


Fig. A8. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

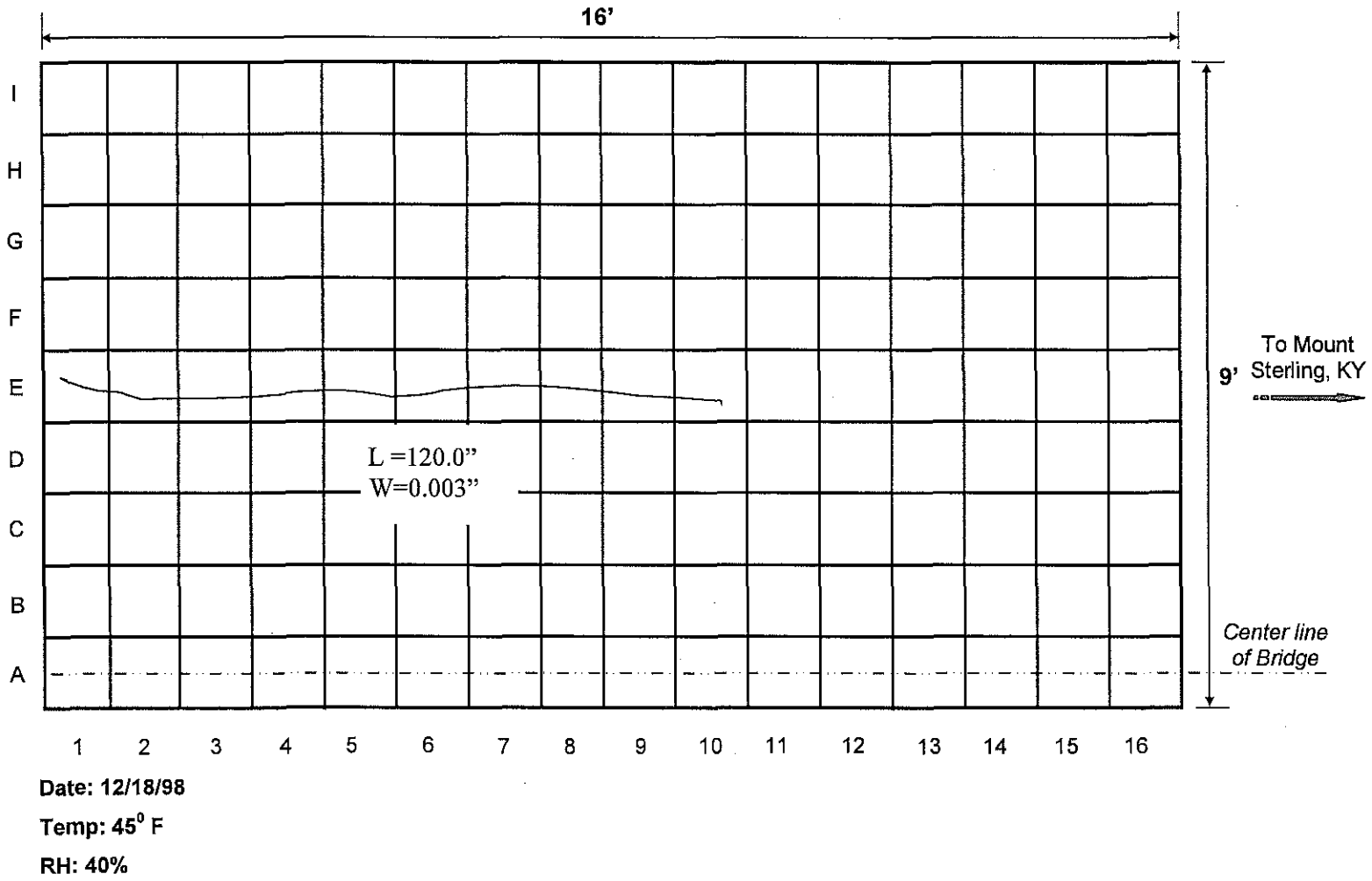


Fig. A9. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

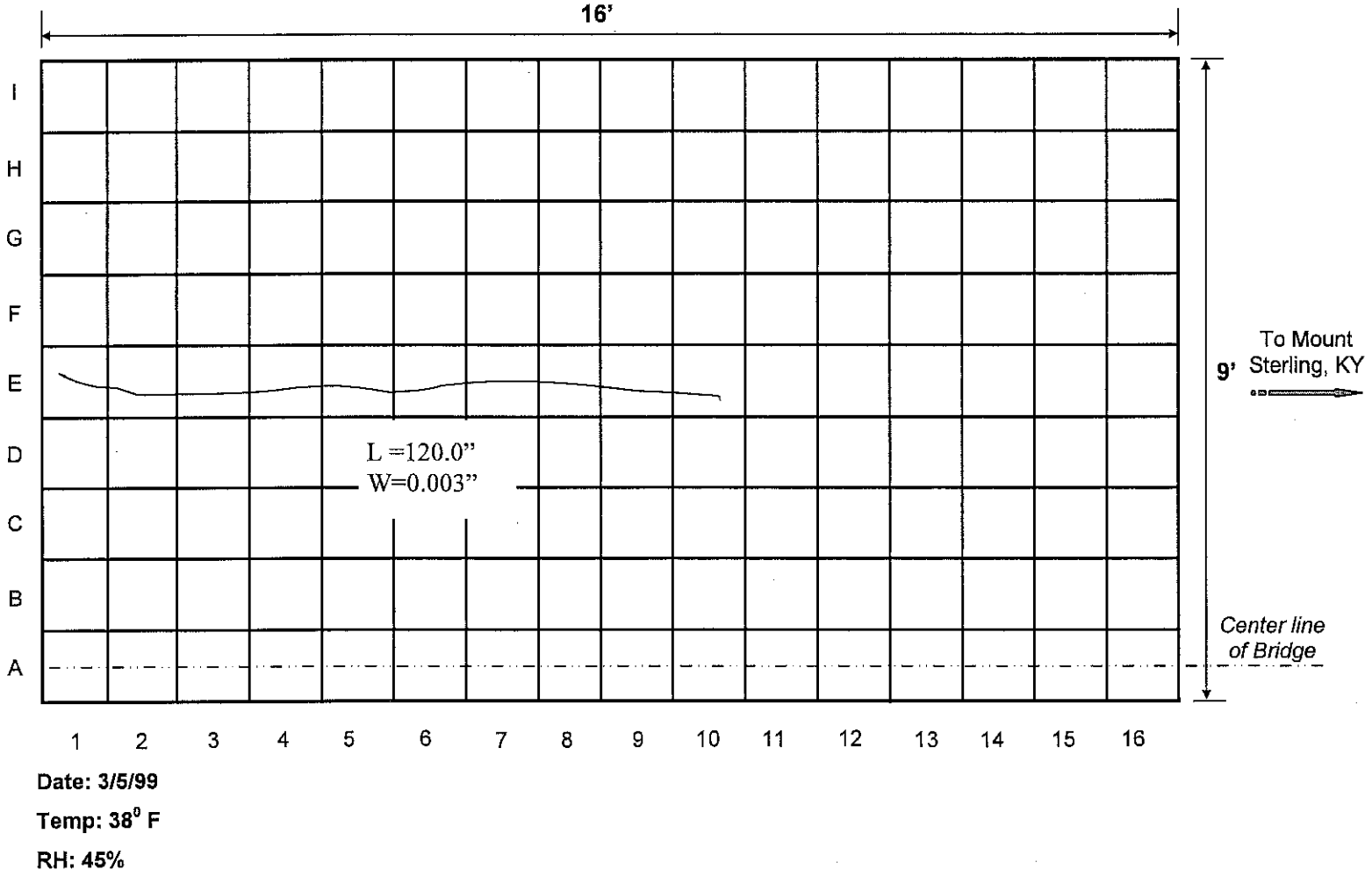


Fig. A10. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

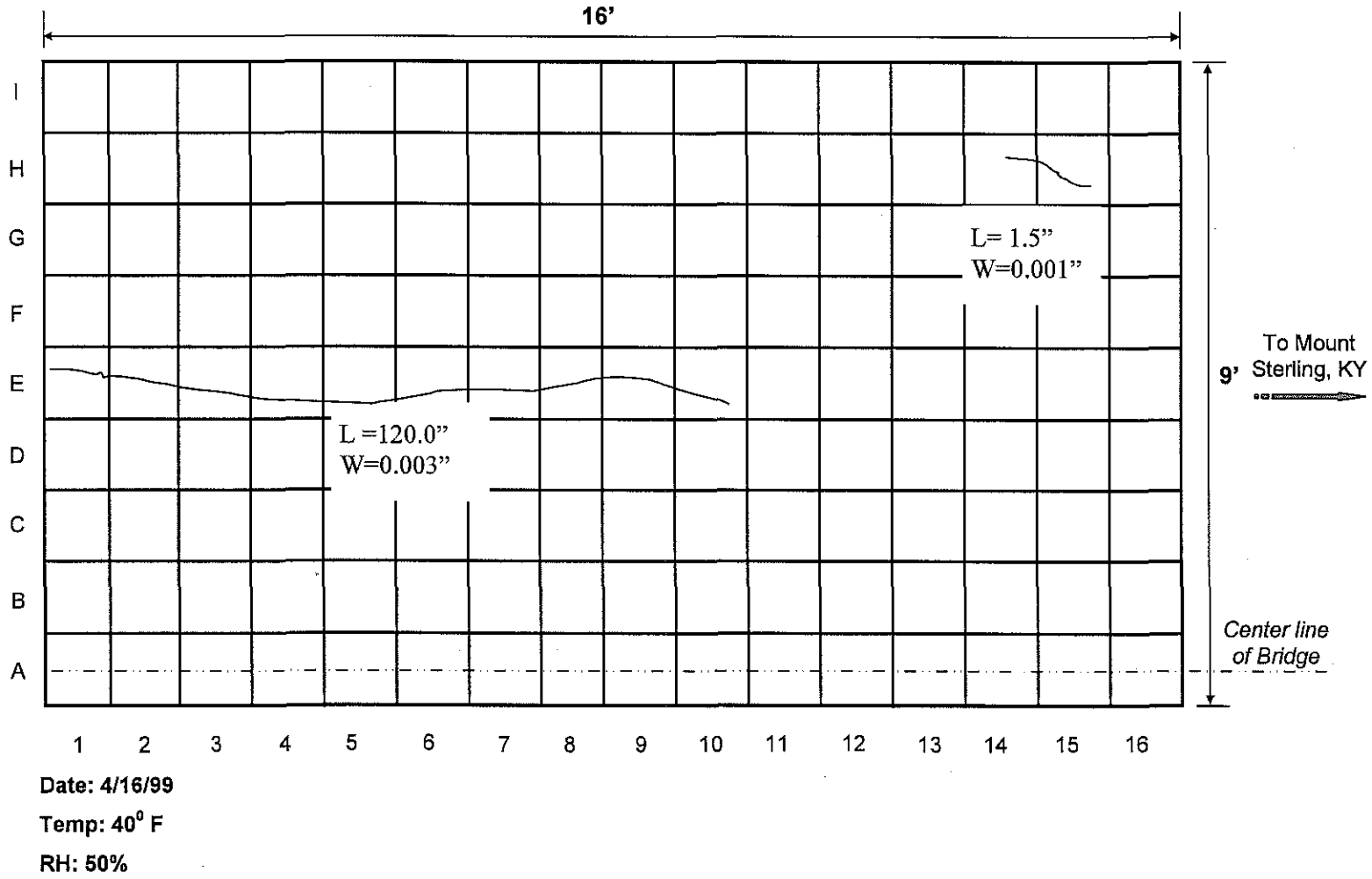


Fig. A11. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

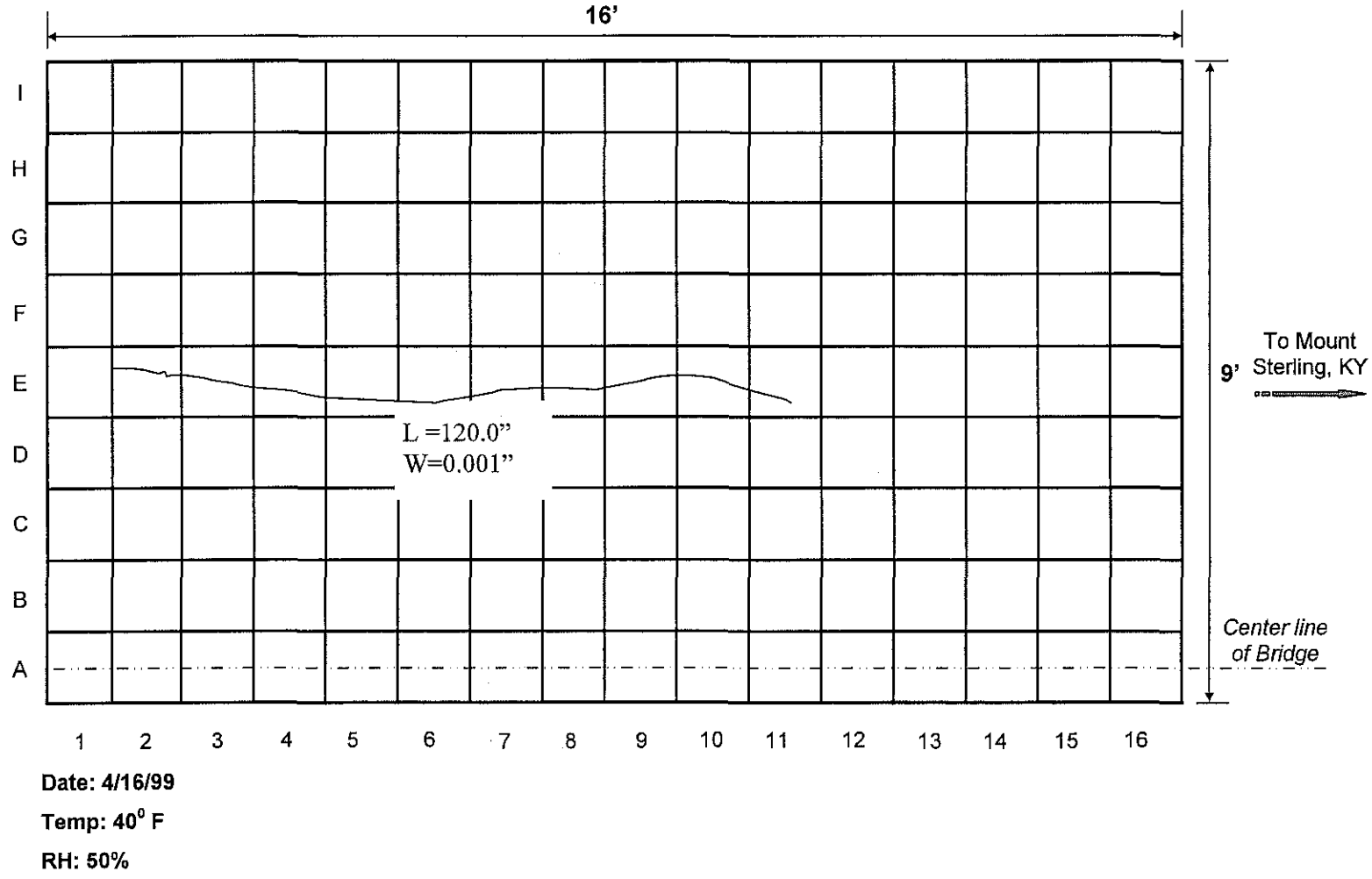


Fig. A12. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

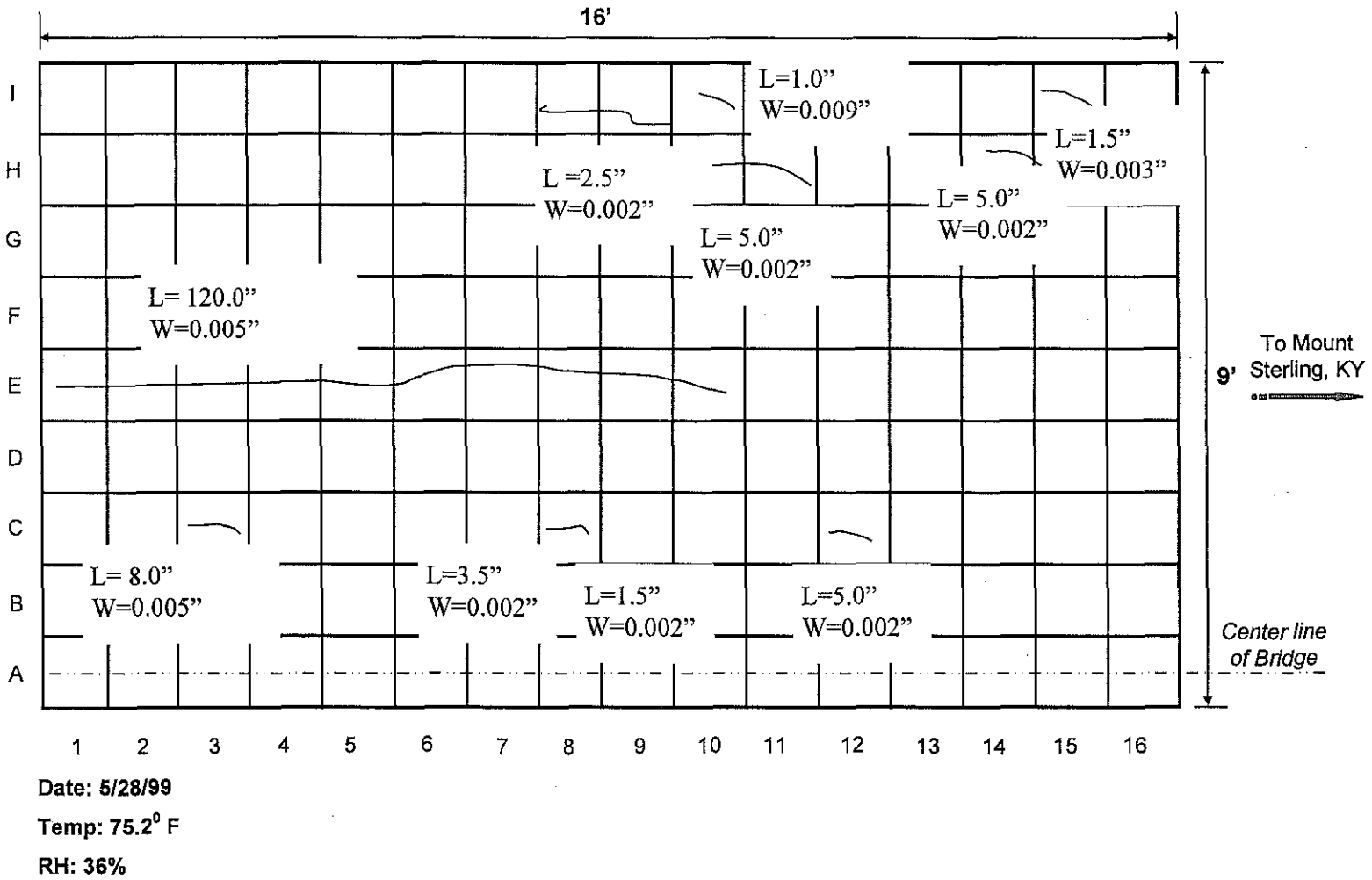
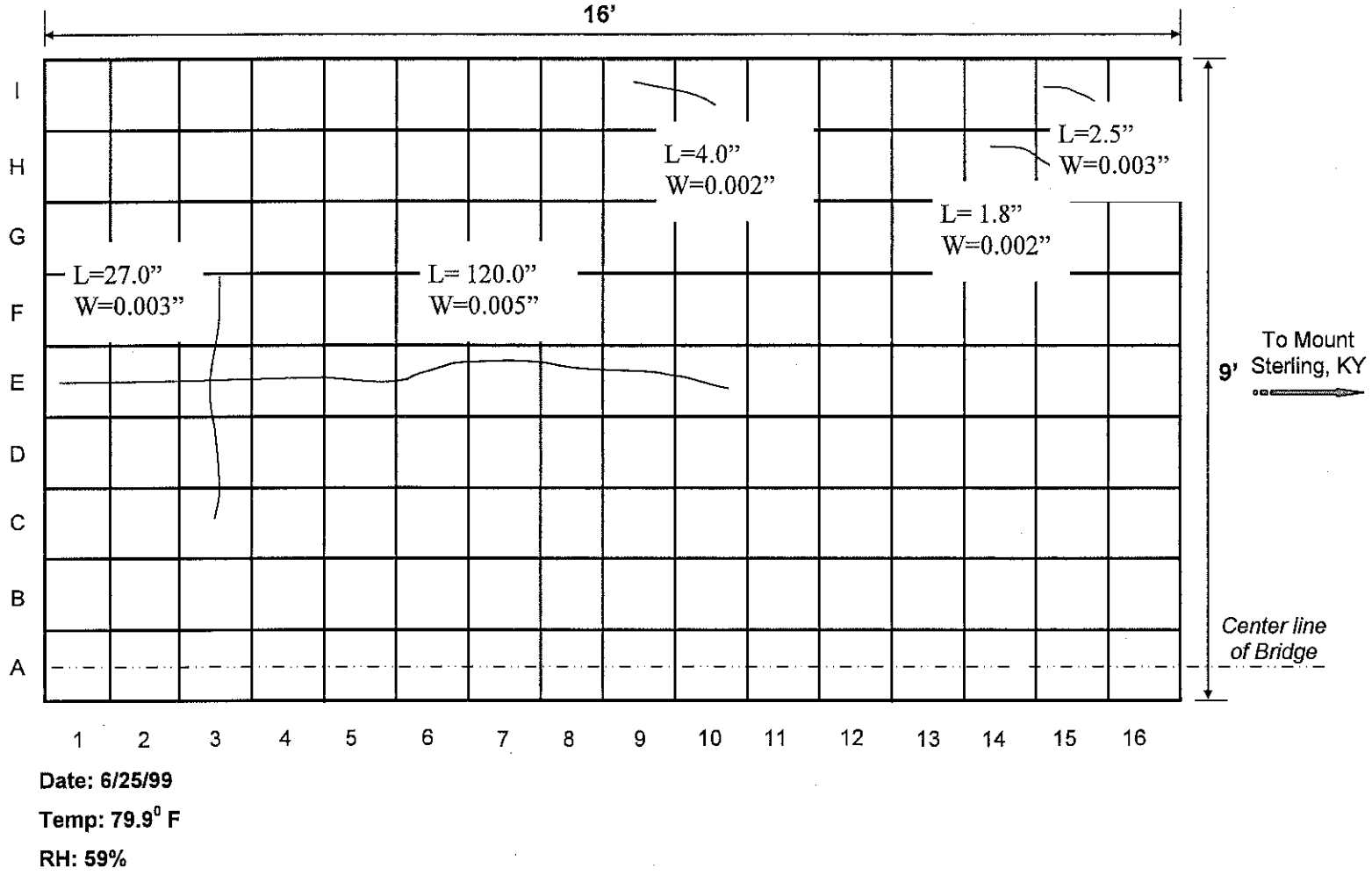


Fig. A13. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition



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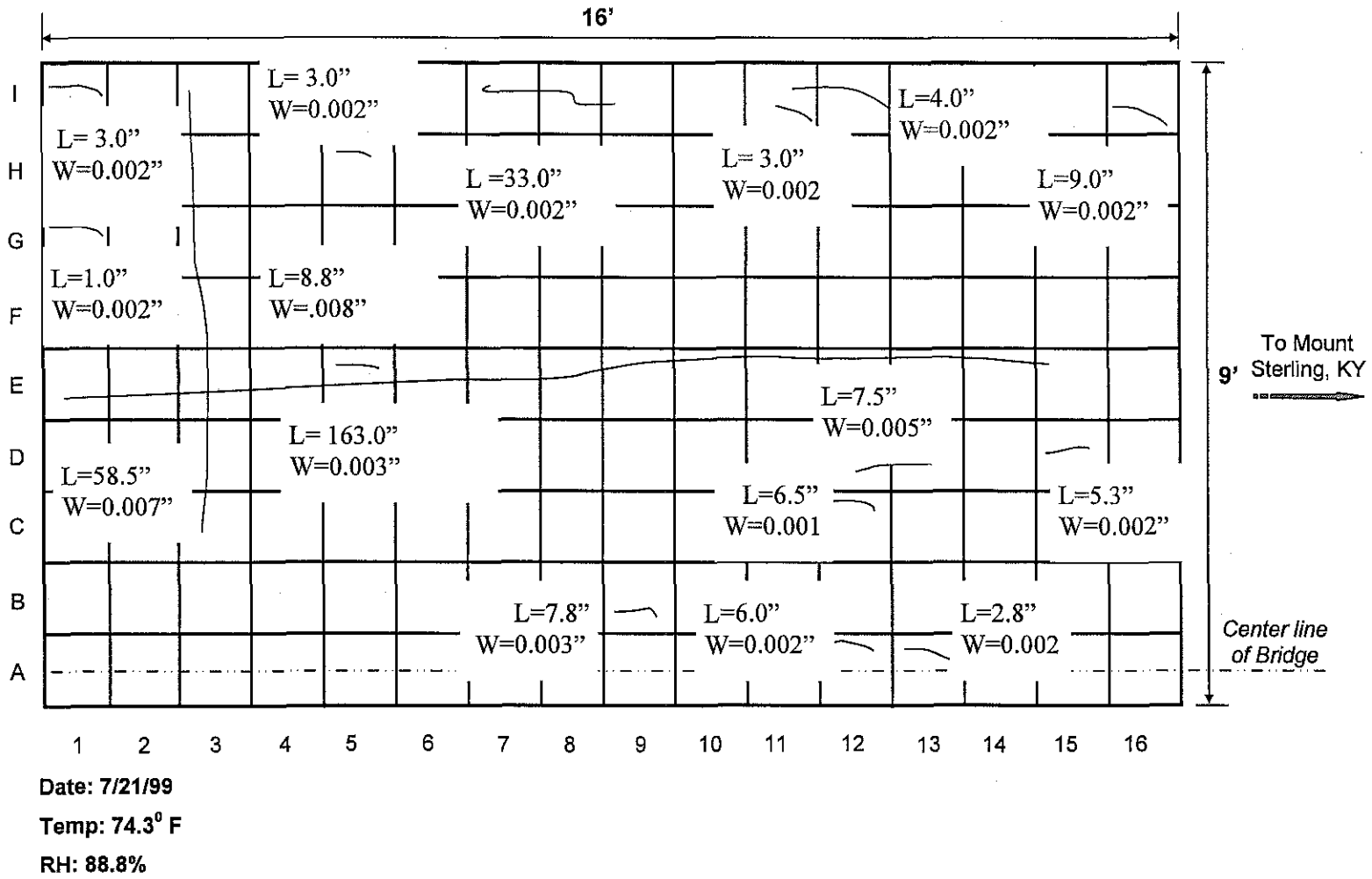

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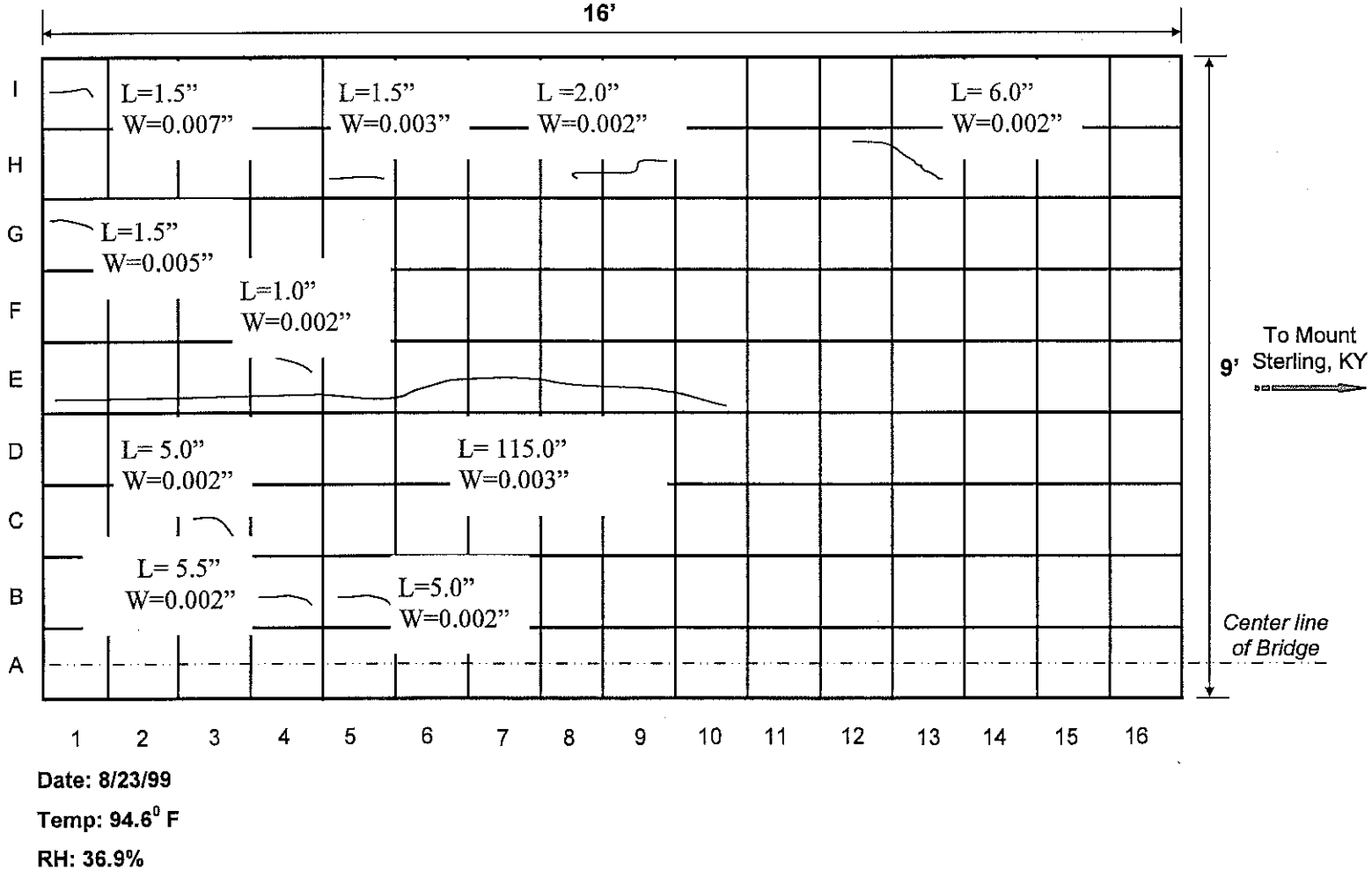

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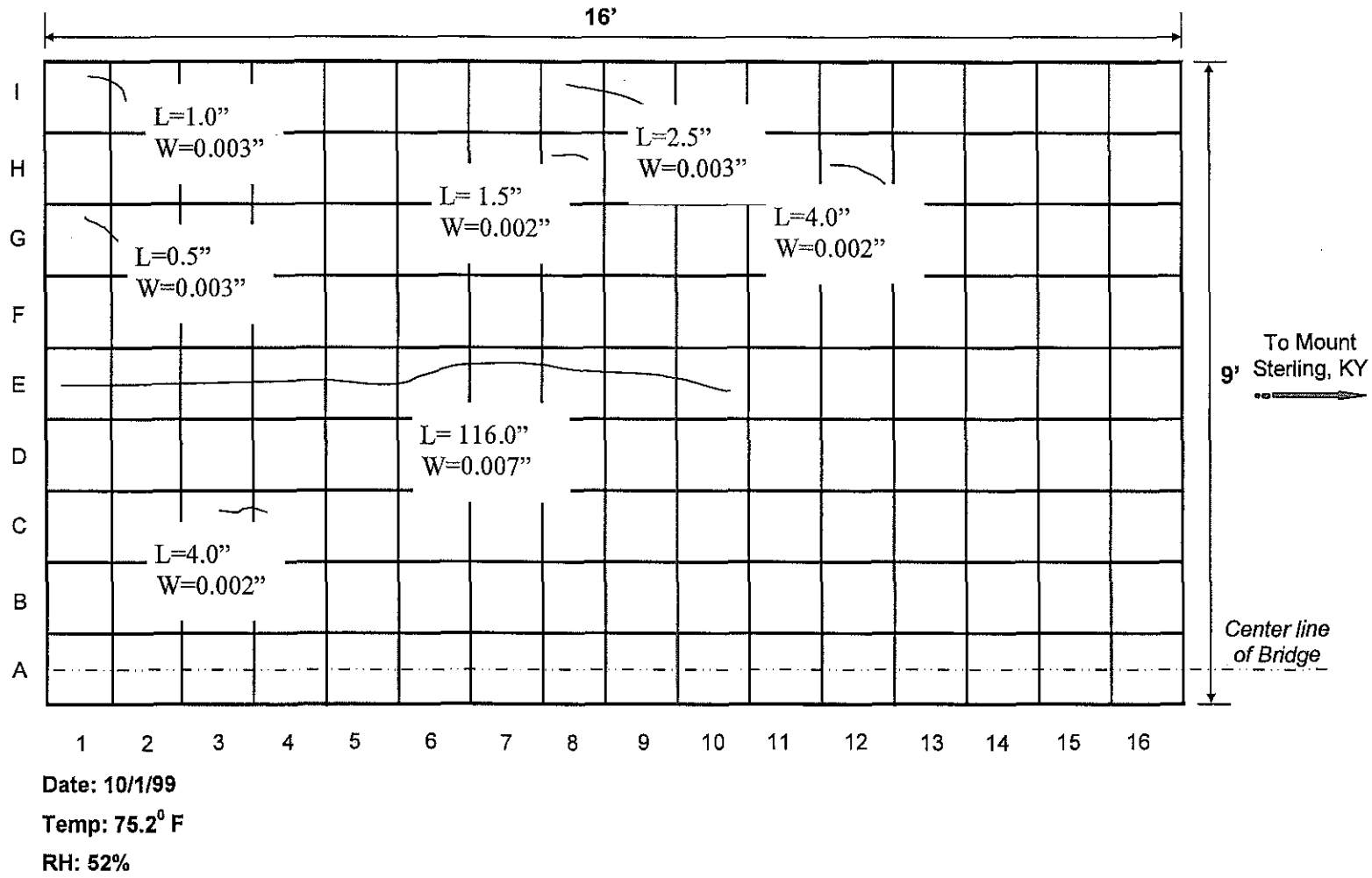

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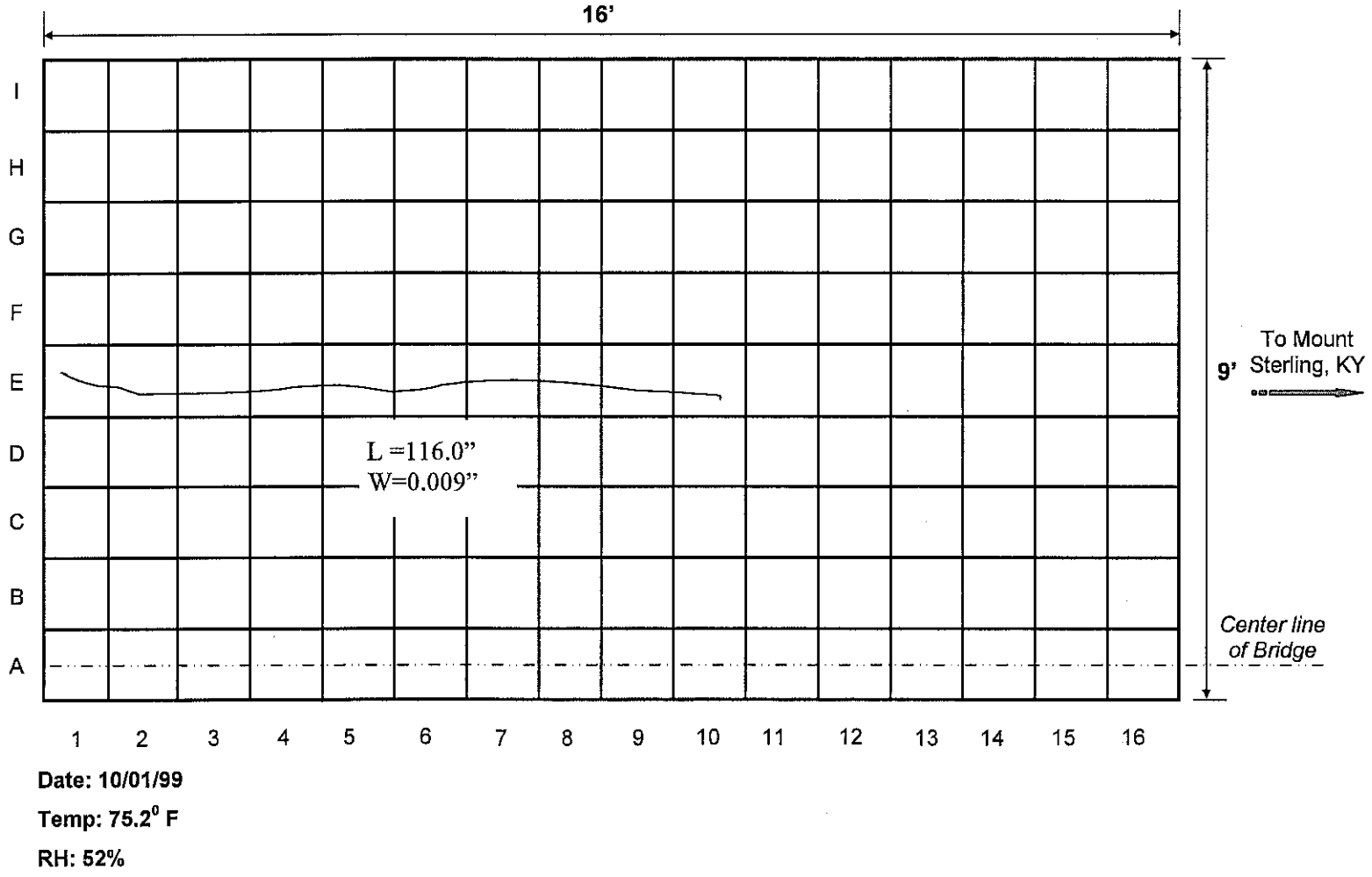

Fig. A18. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

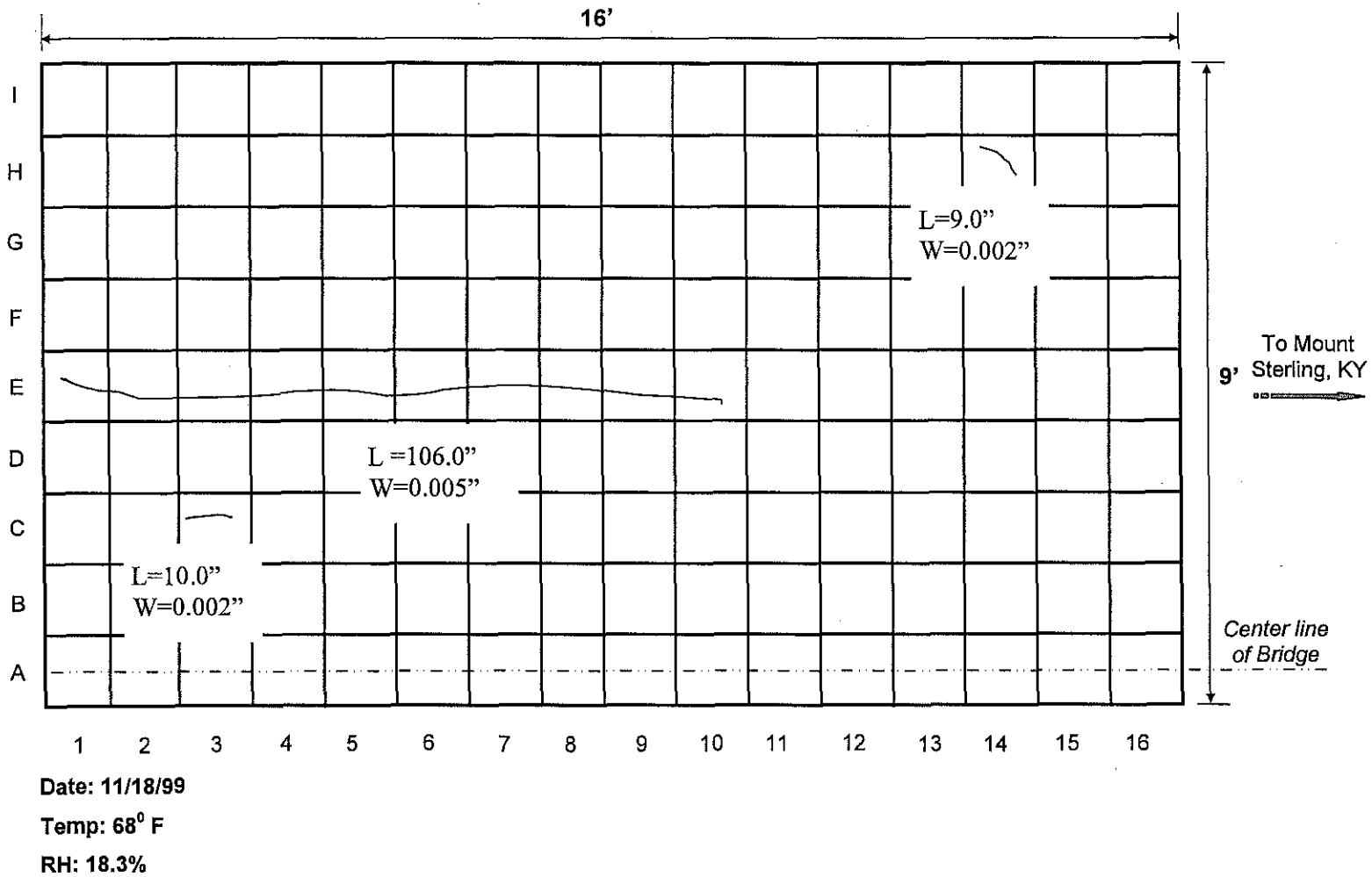

Fig. A19. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

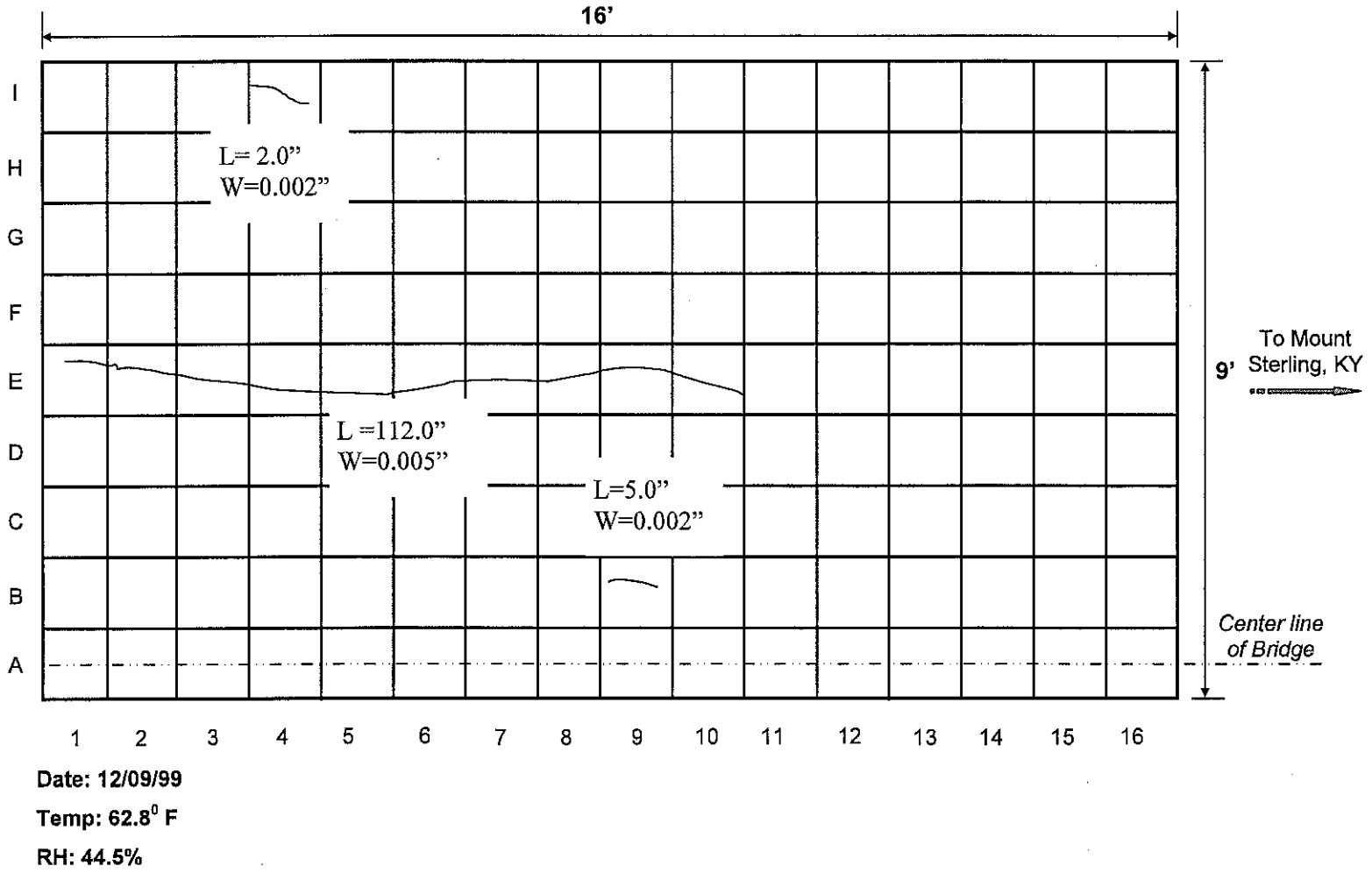

Fig. A20. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

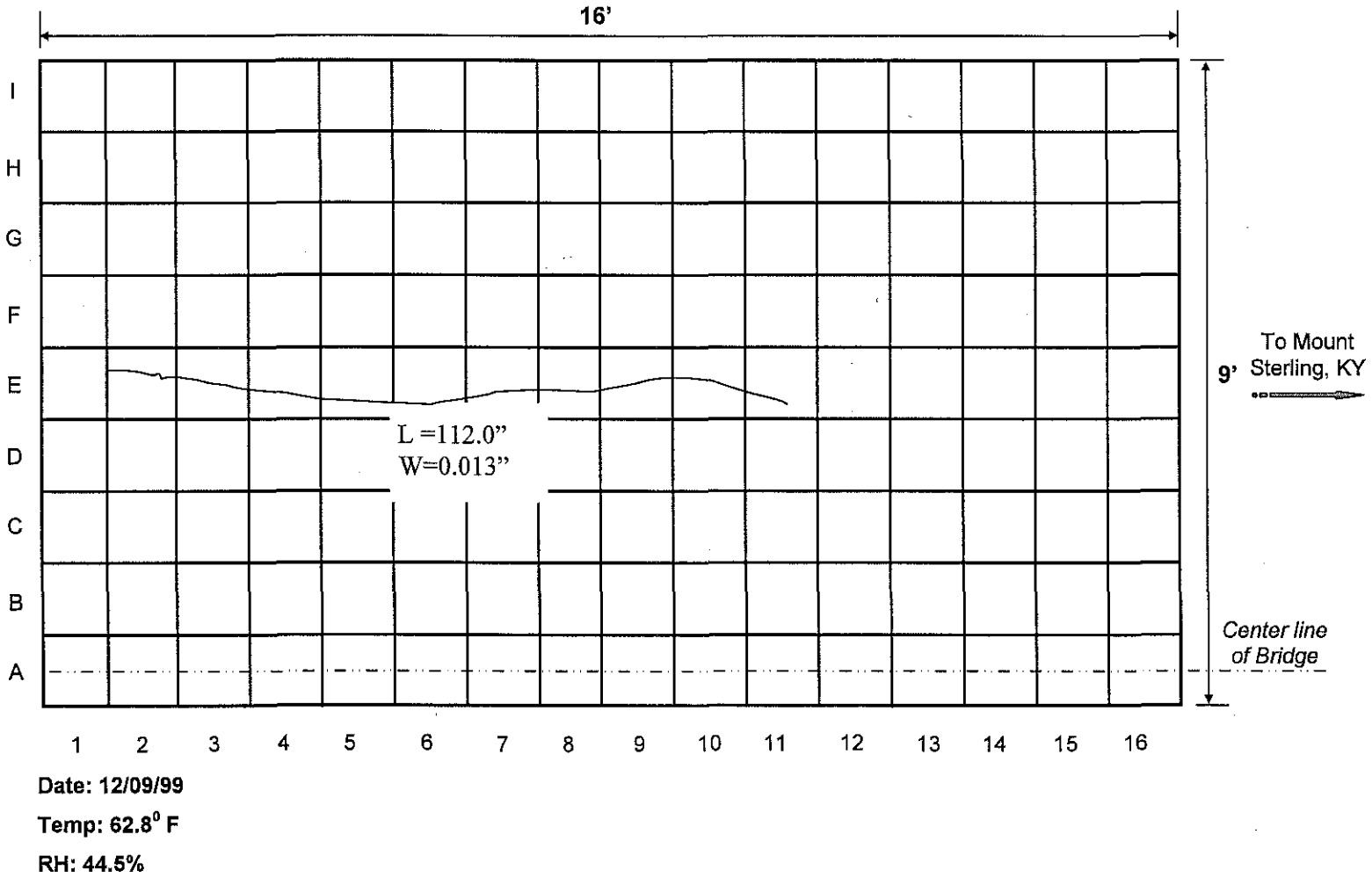

Fig. A21. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

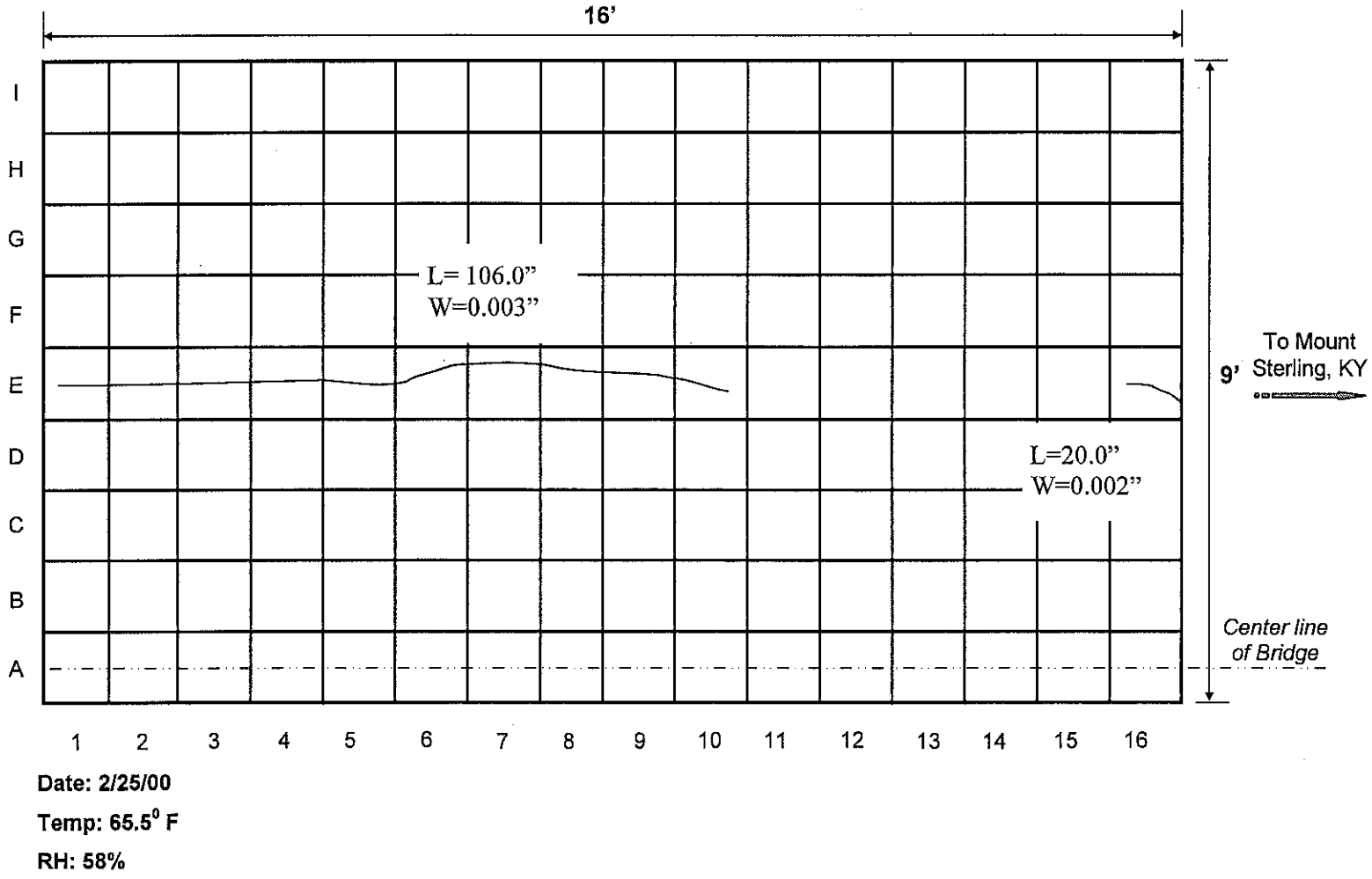

Fig. A22. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

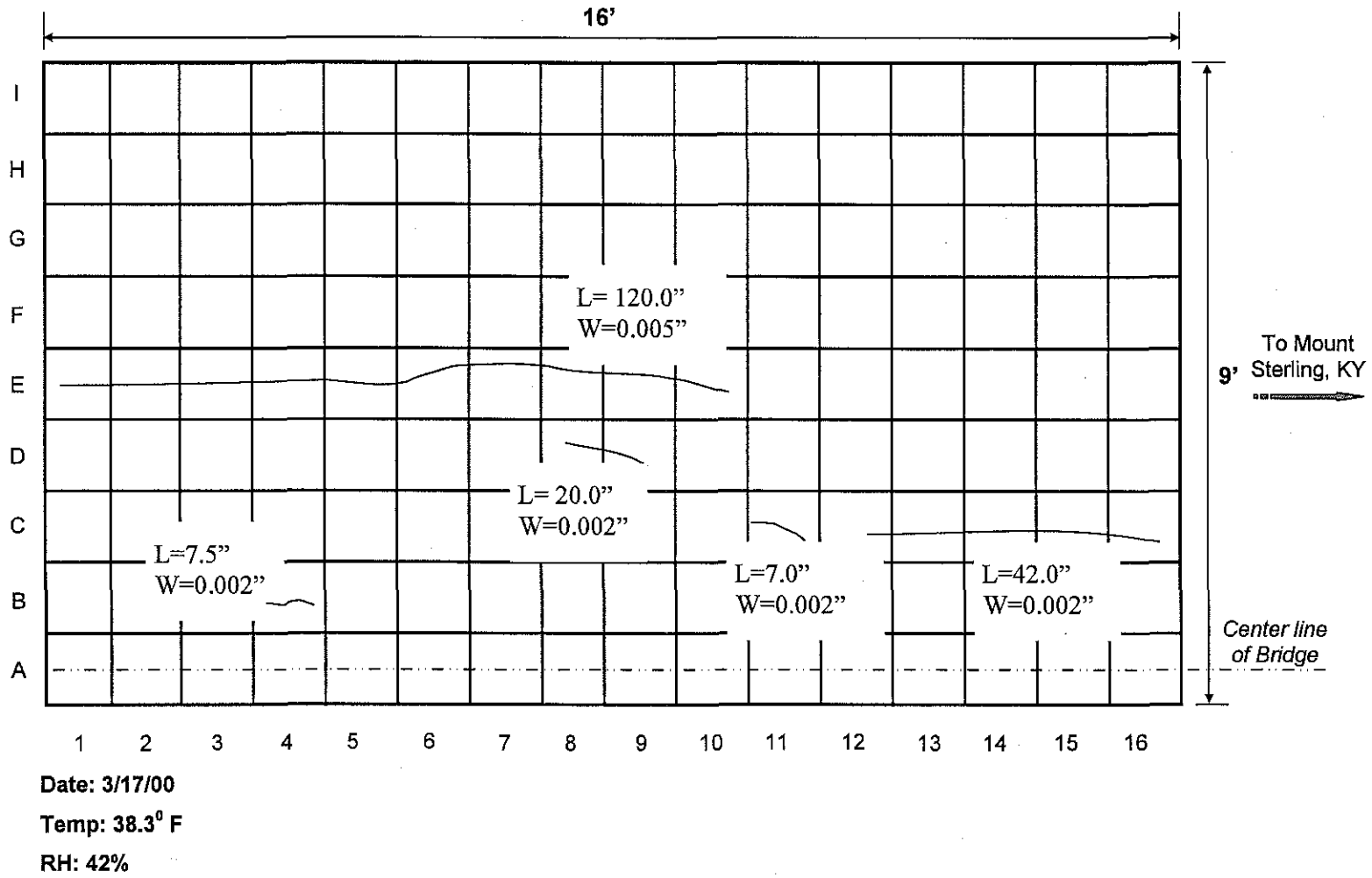

Fig. A23. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

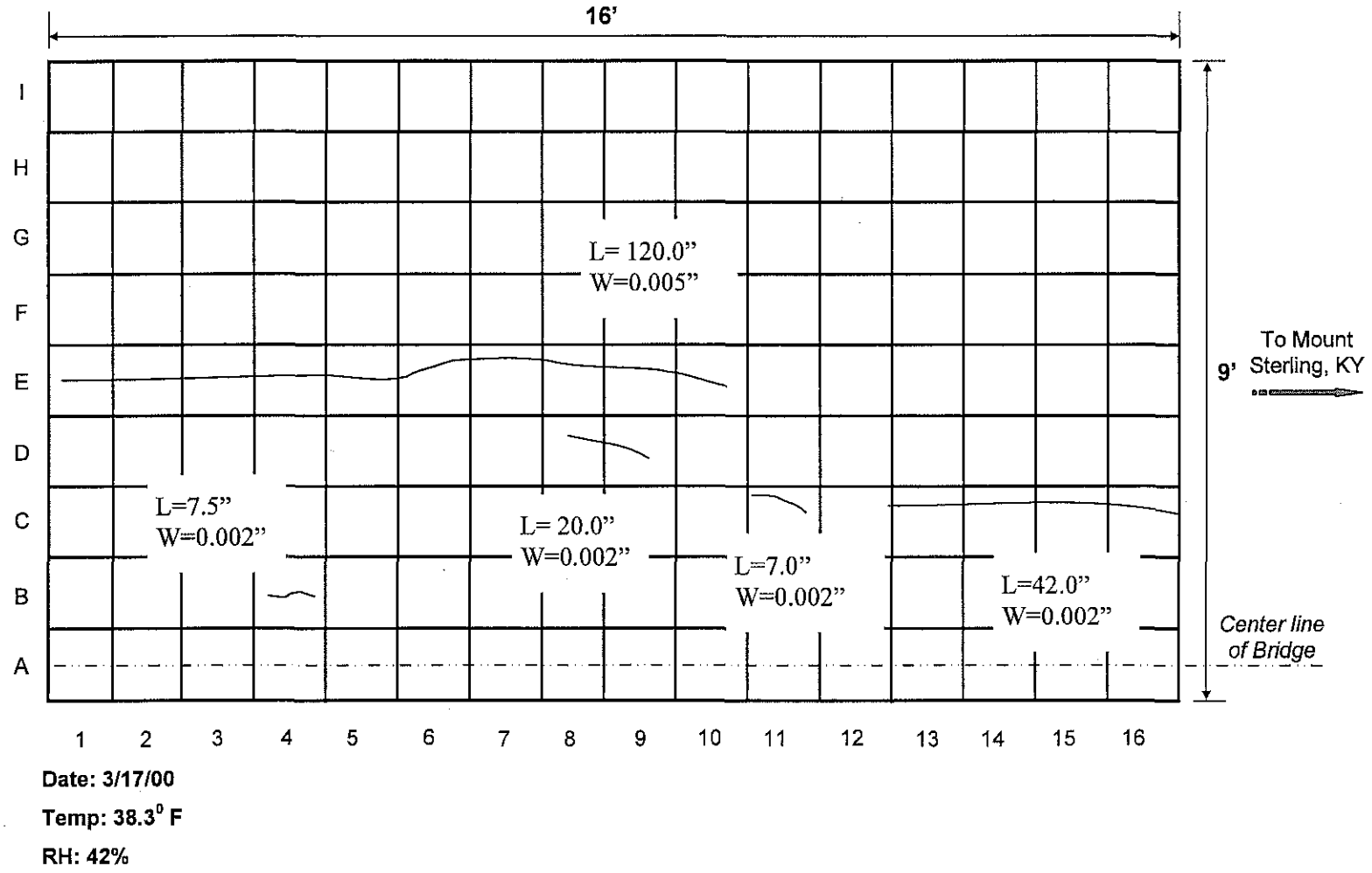

Fig. A24. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

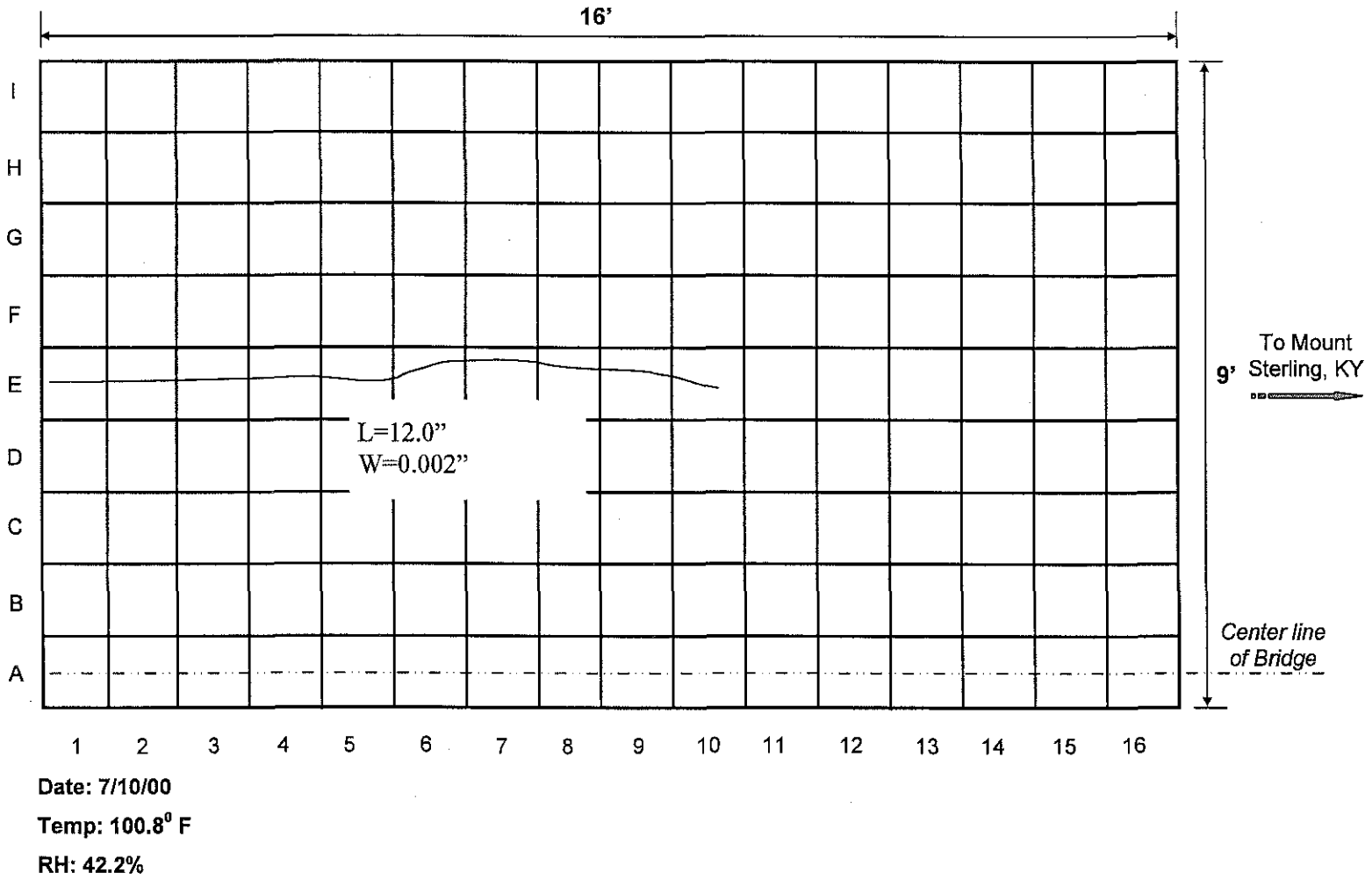

Fig. A25. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

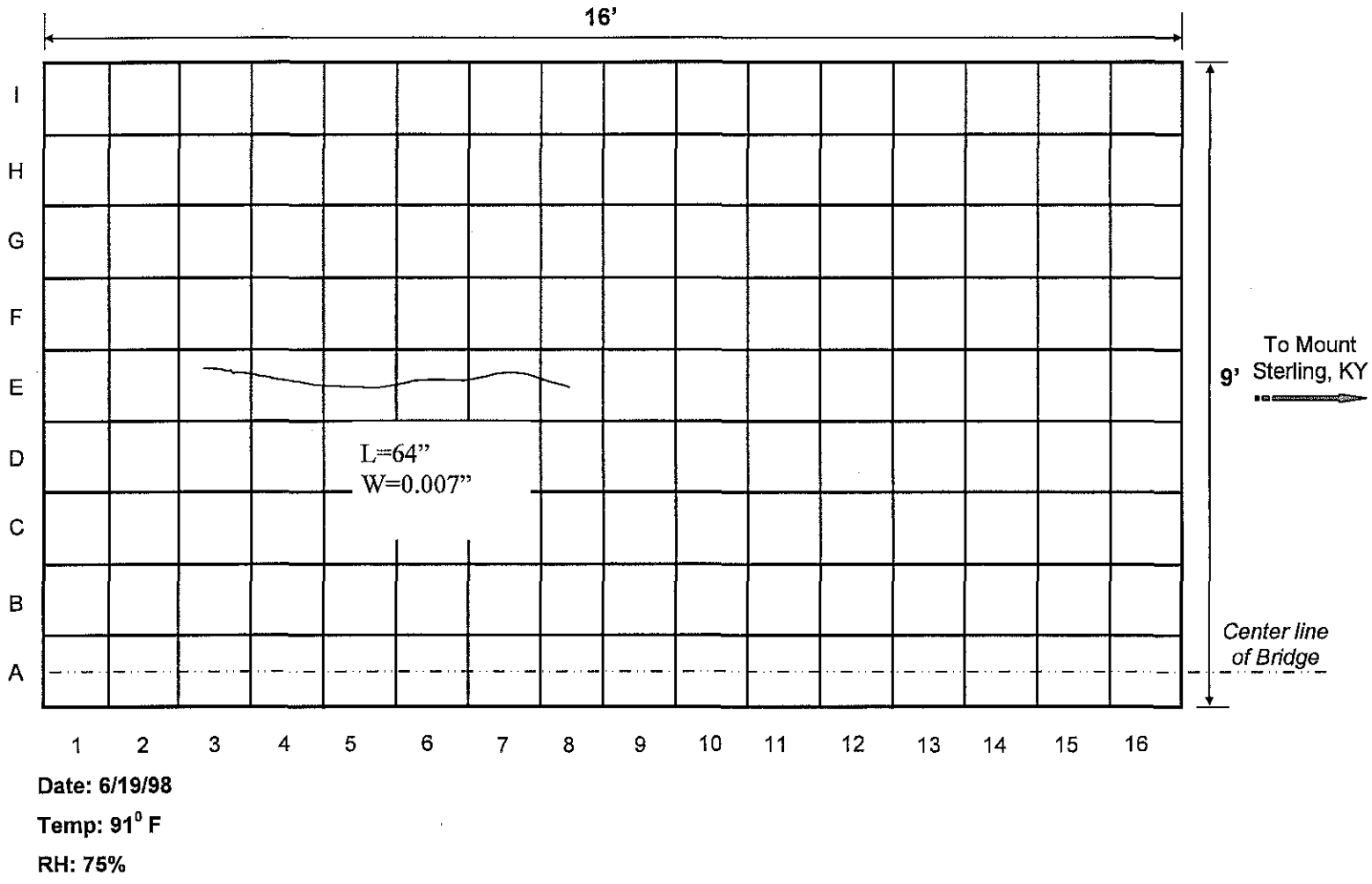

Fig. A26. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

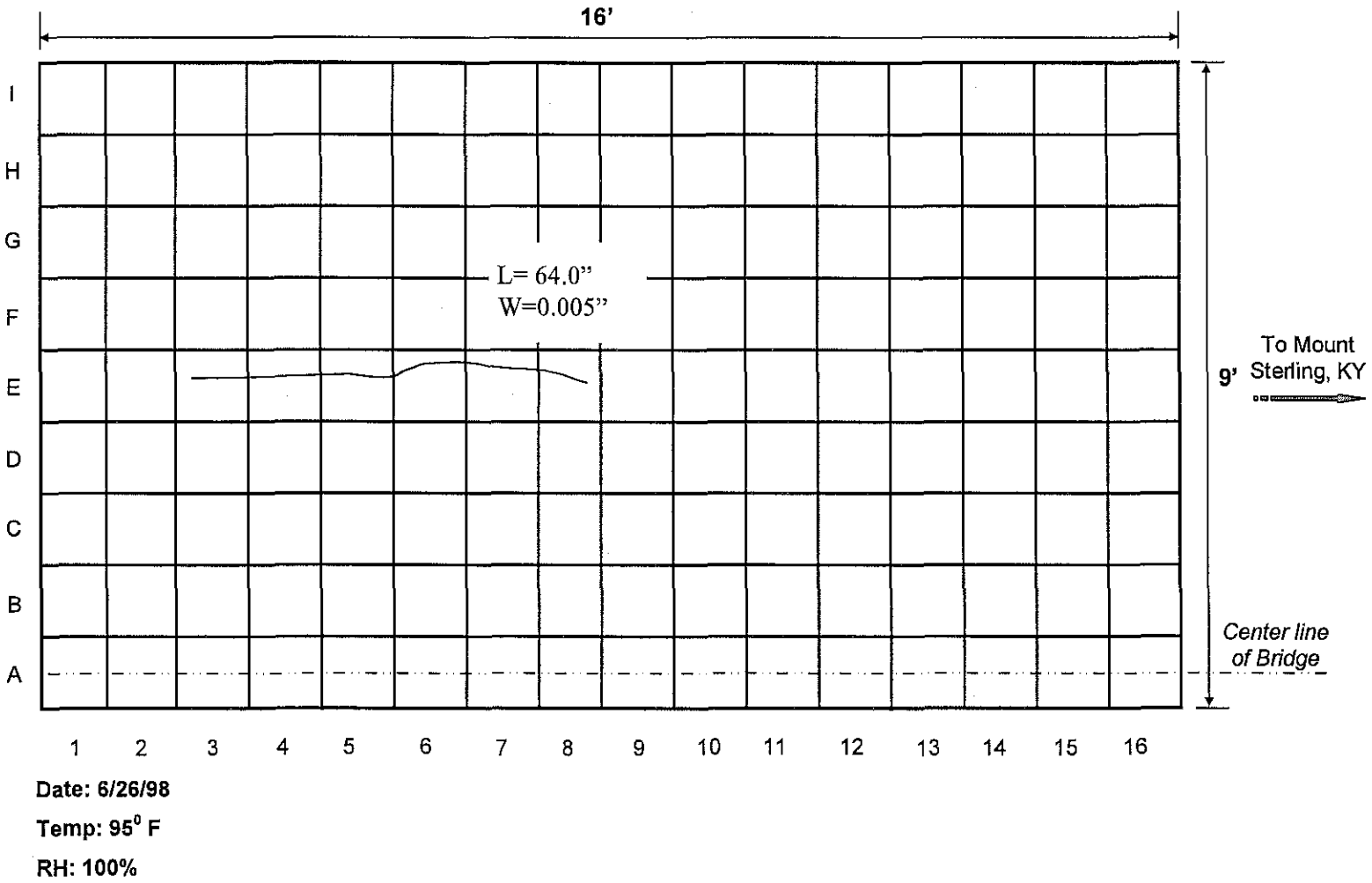

Fig. A27. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

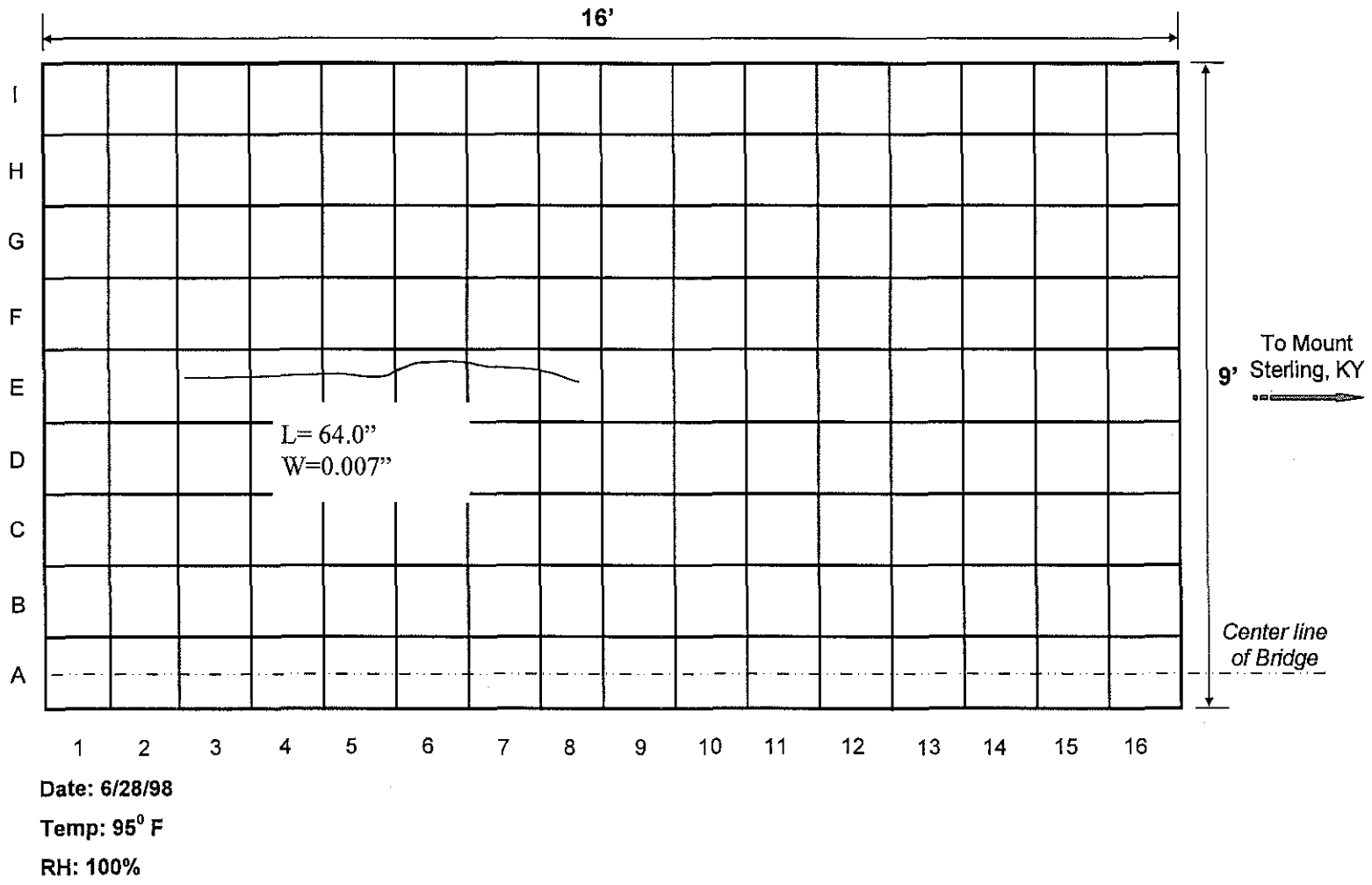

Fig. A28. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

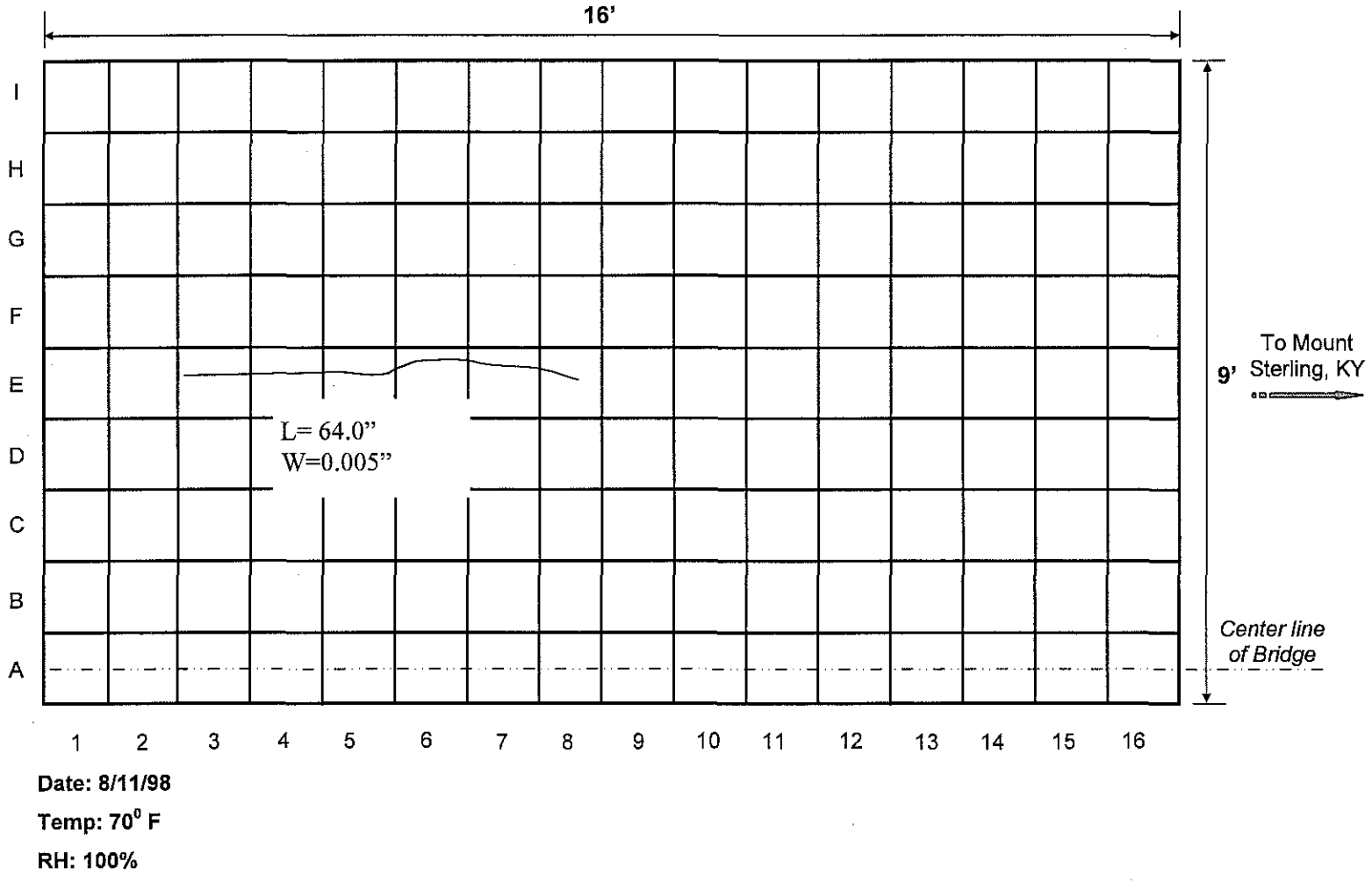

Fig. A29. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

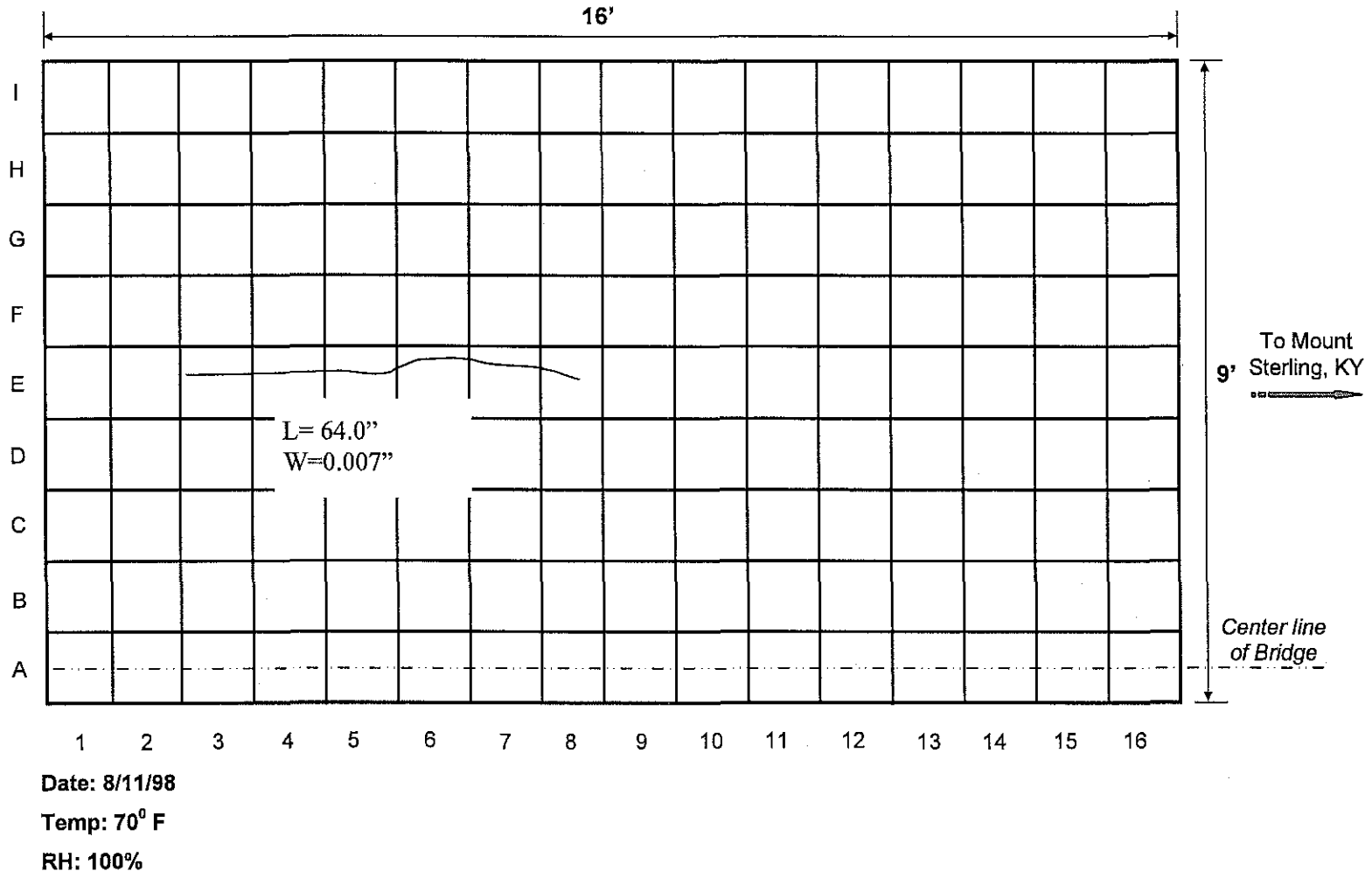

Fig. A30. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

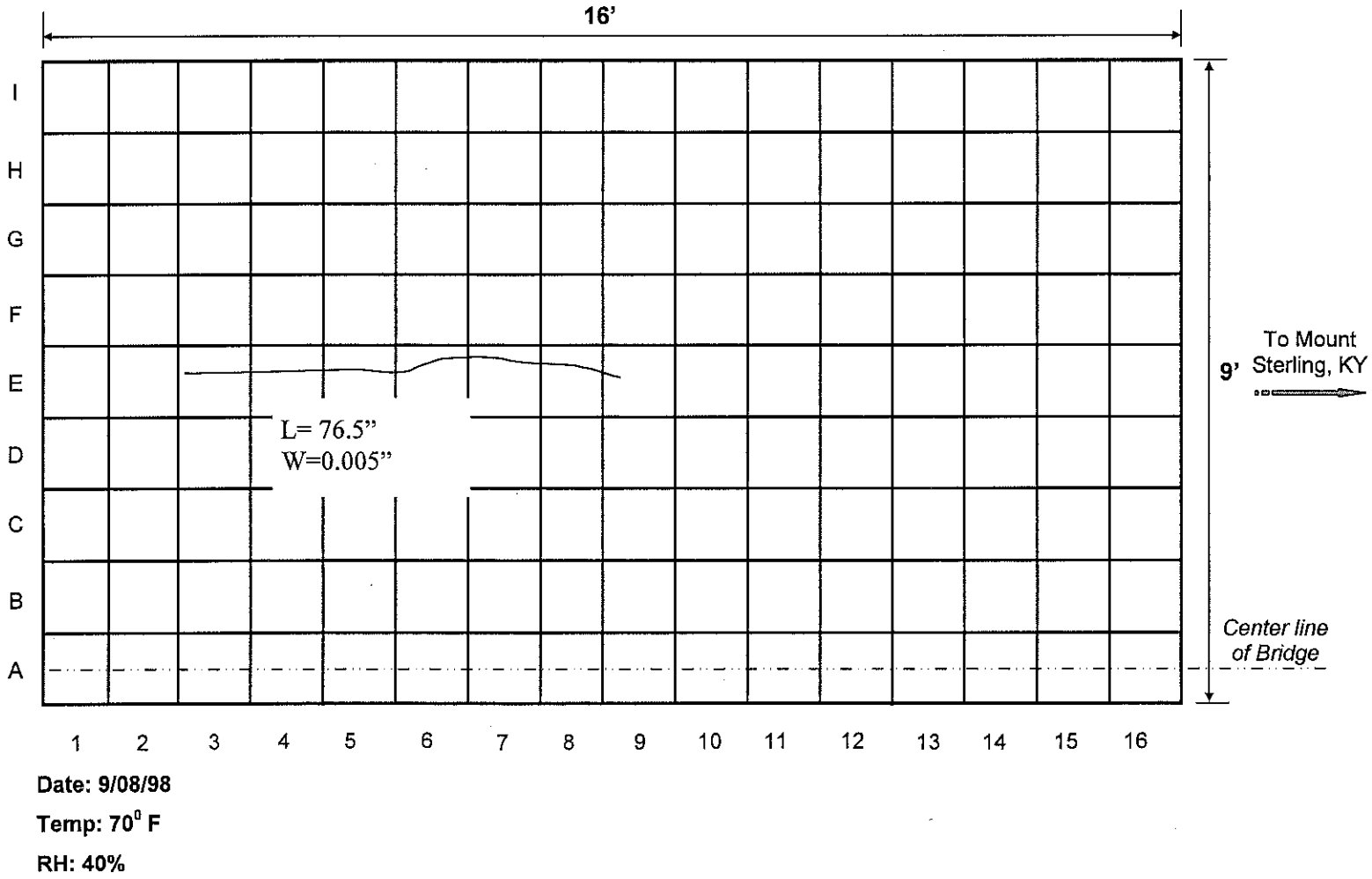

Fig. A31. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

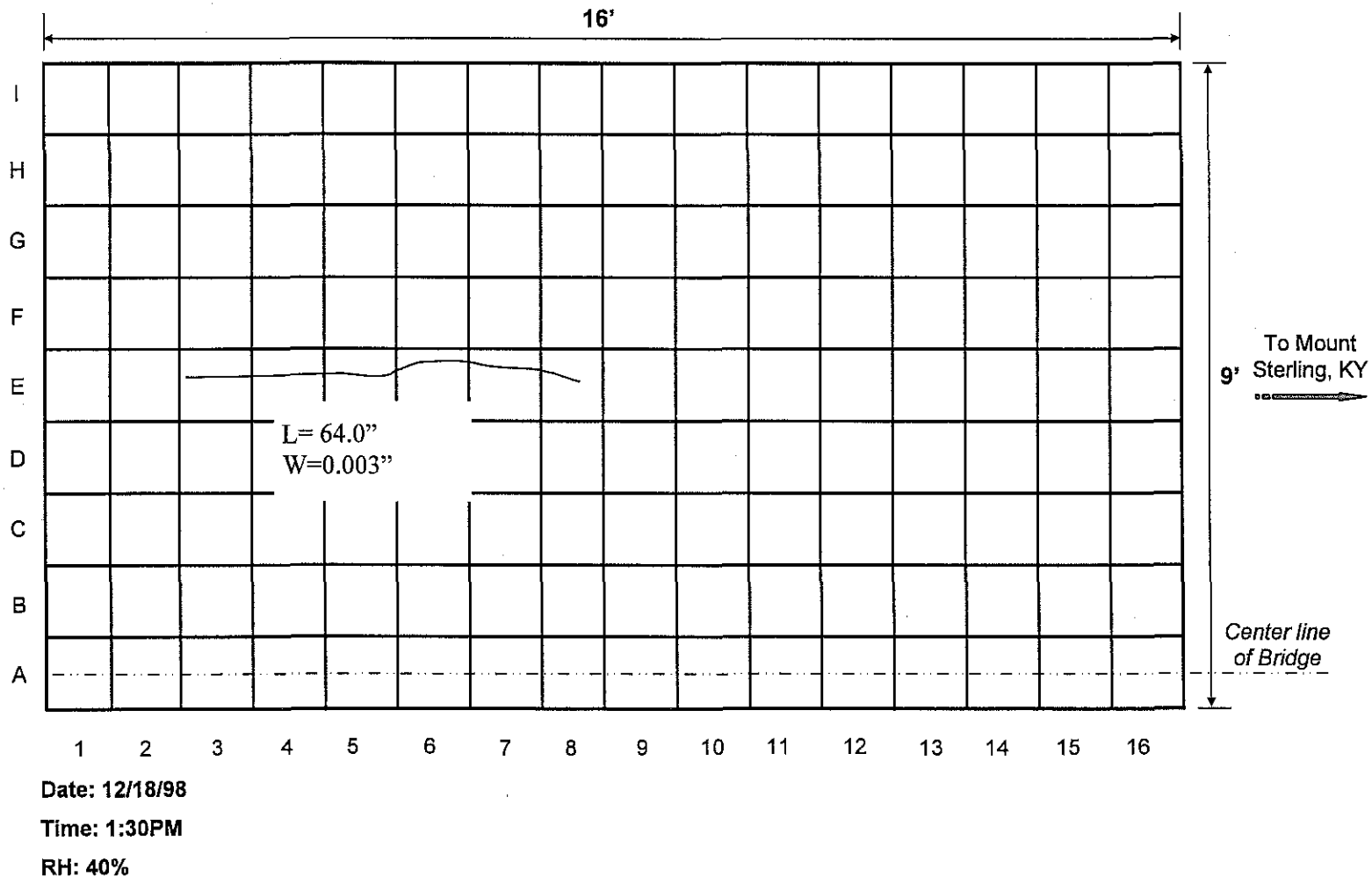

Fig. A32. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

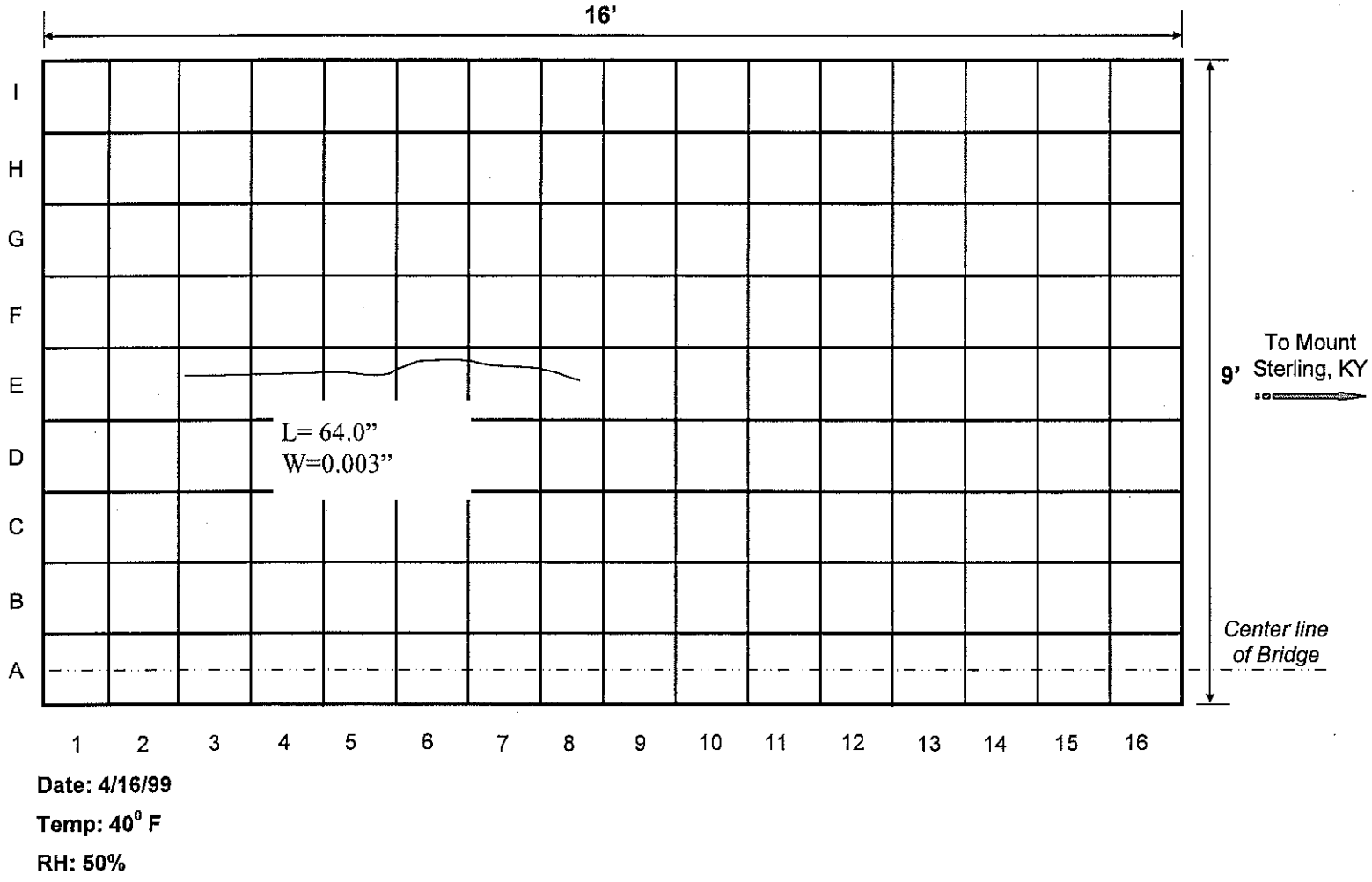

Fig. A33. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

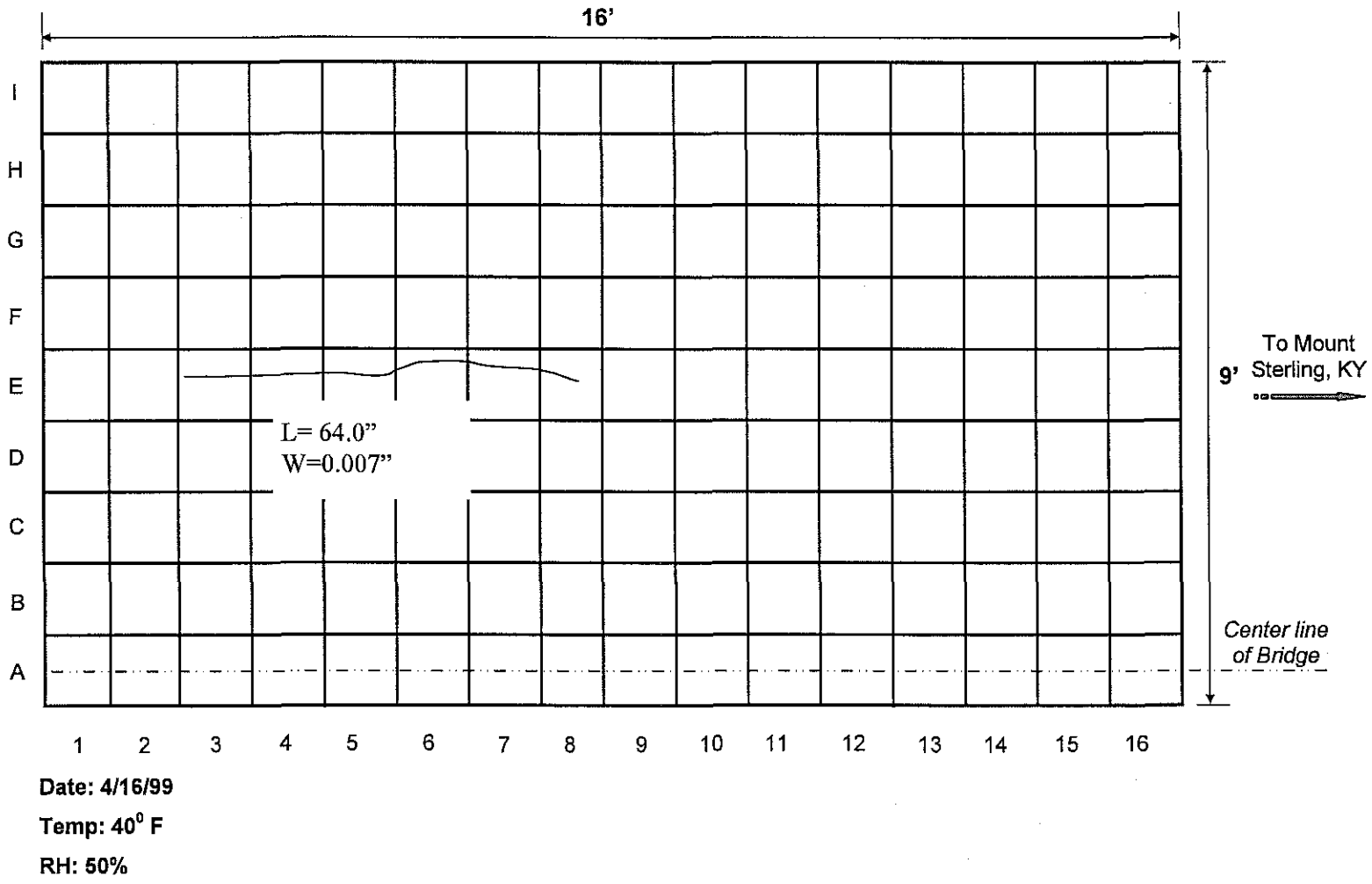

Fig. A34. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

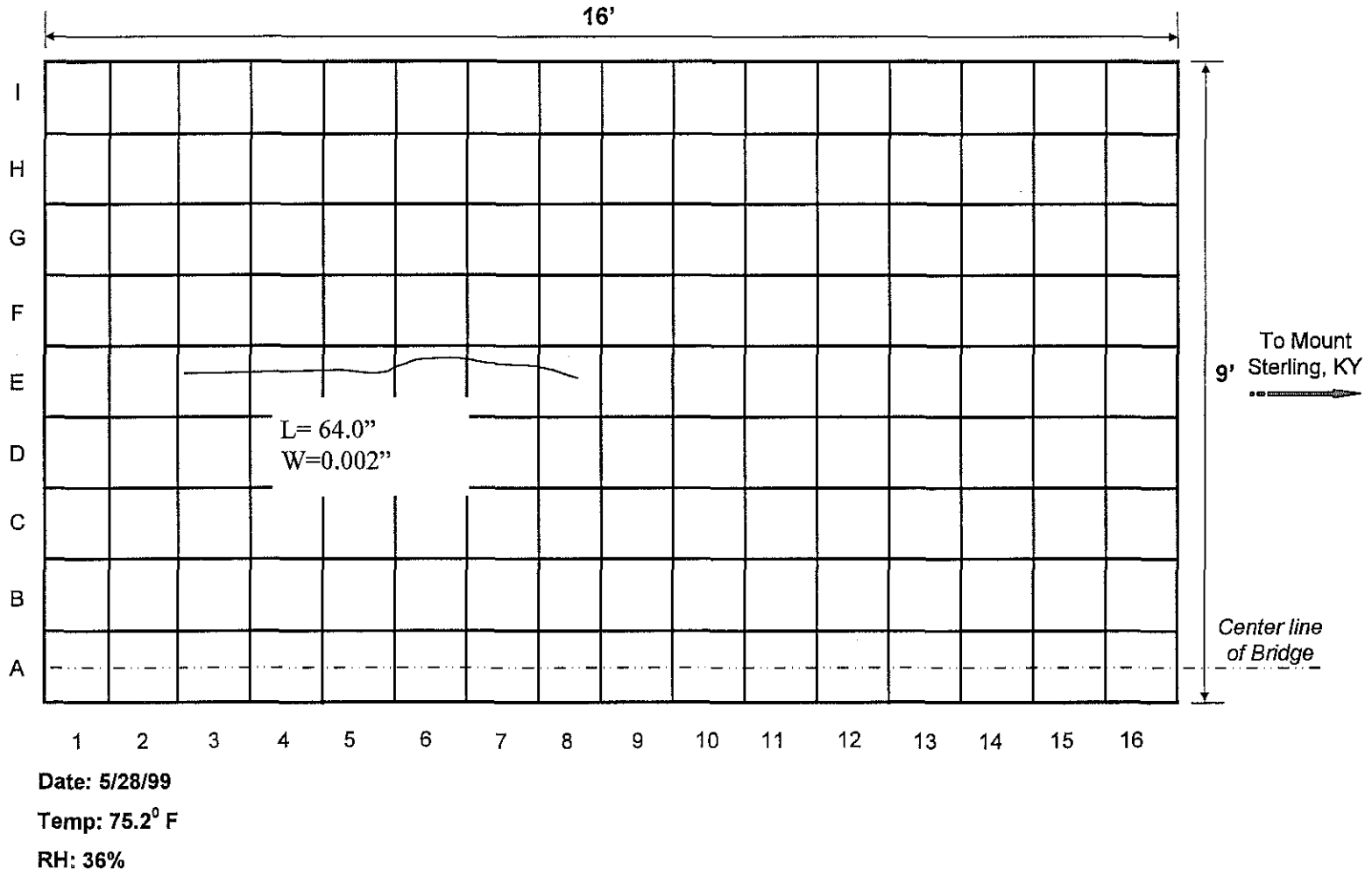

Fig. A35. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

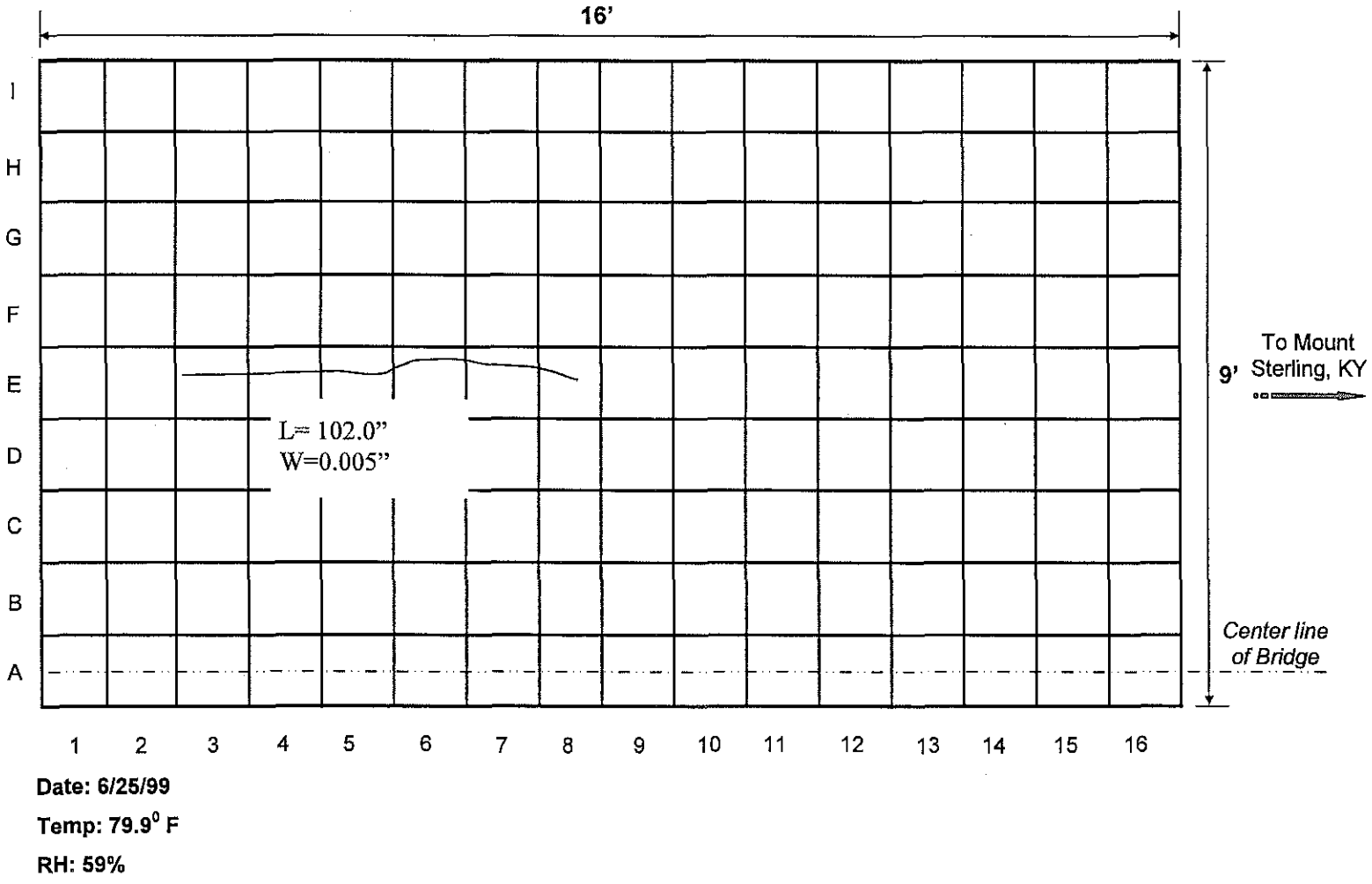

Fig. A36. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

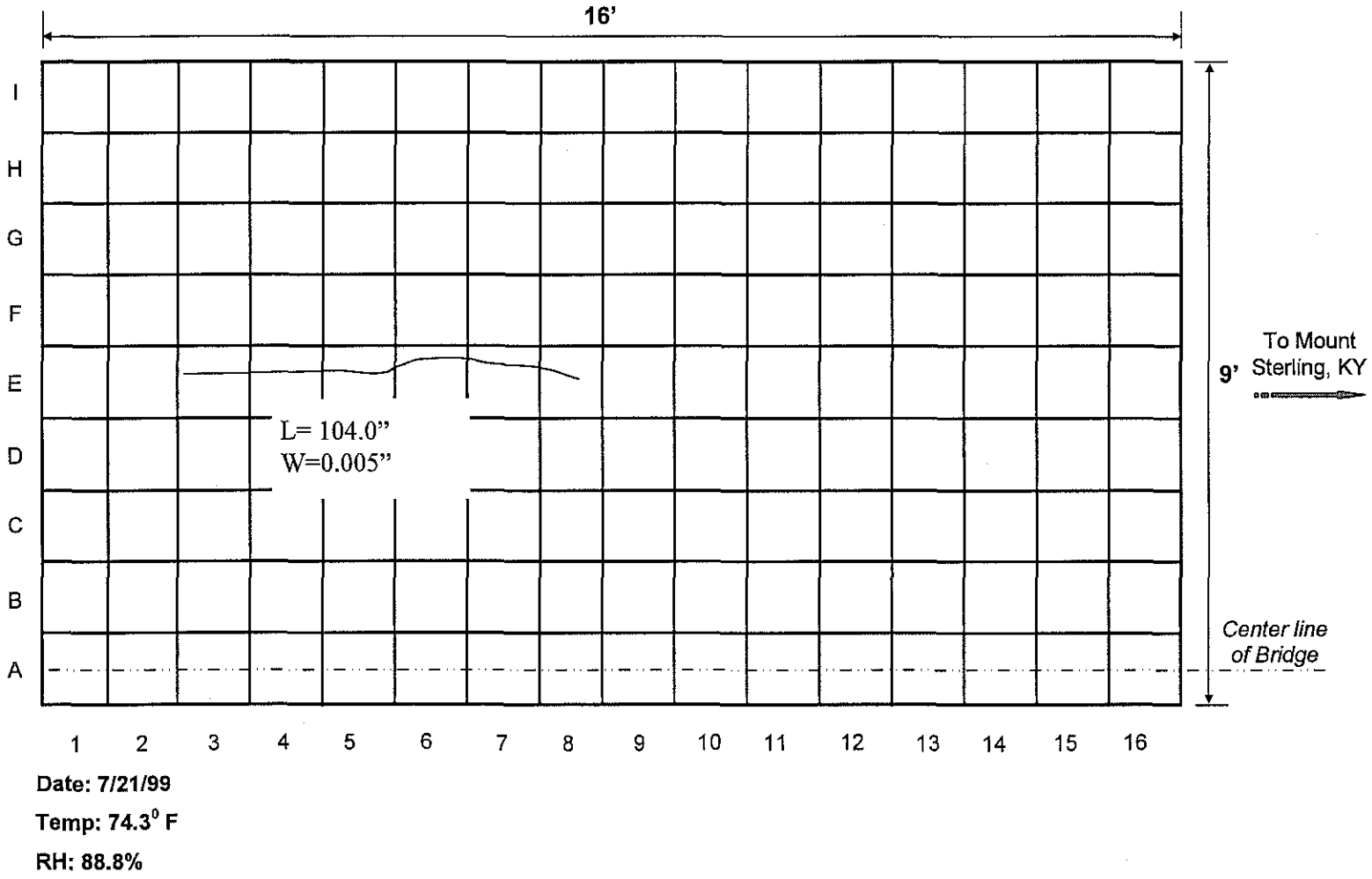

Fig. A37. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

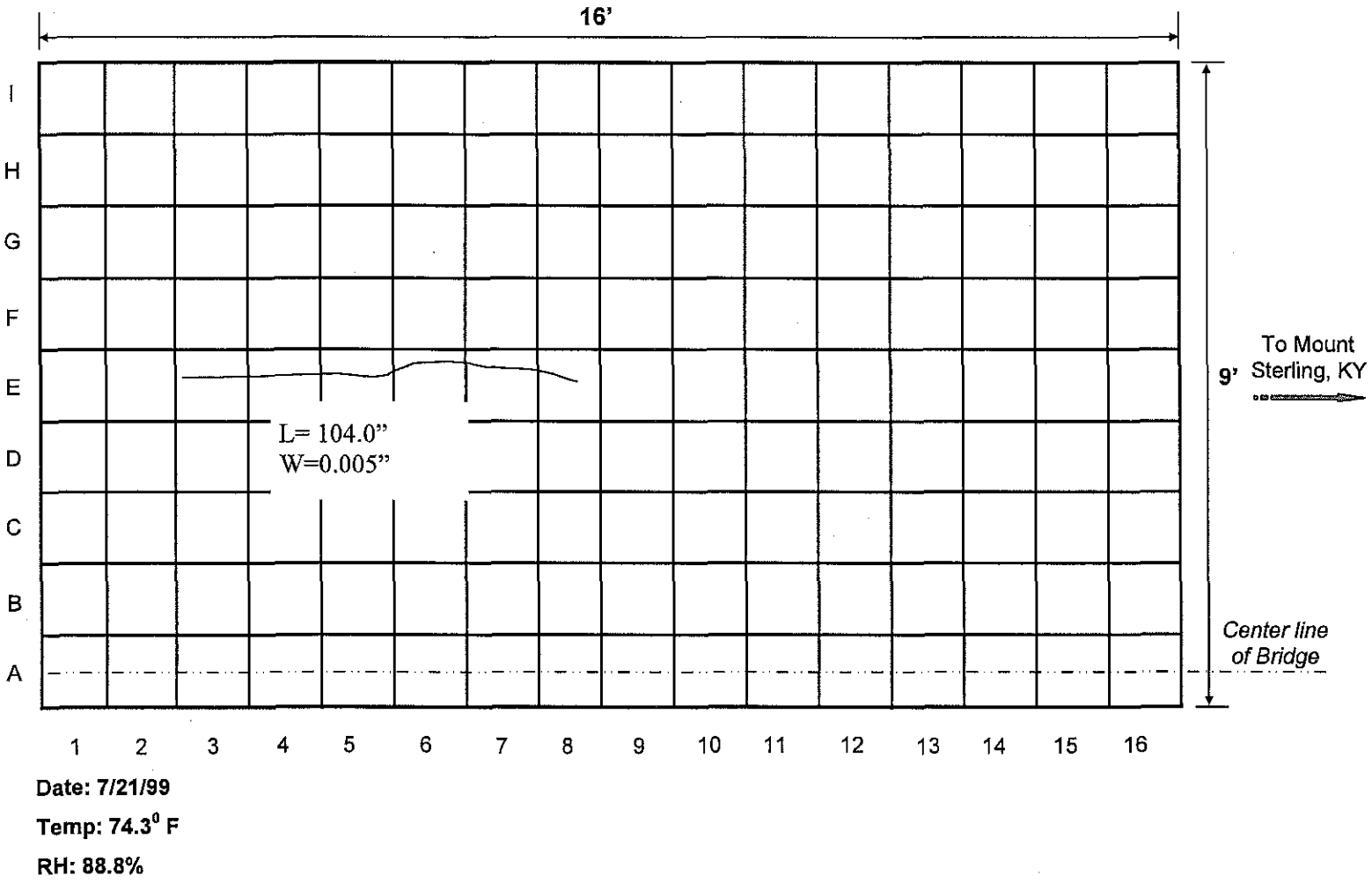

Fig. A38. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

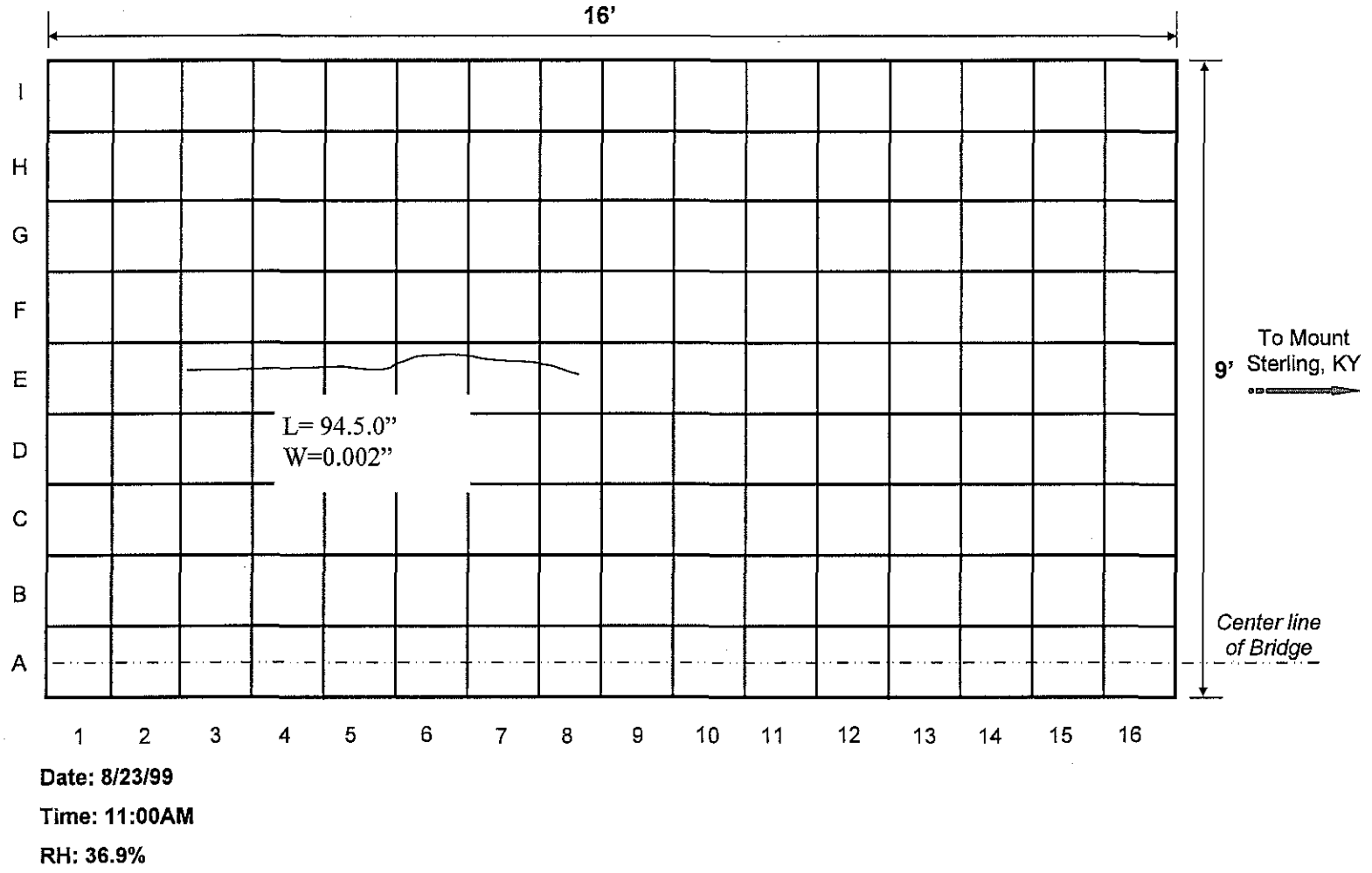

Fig. A39. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

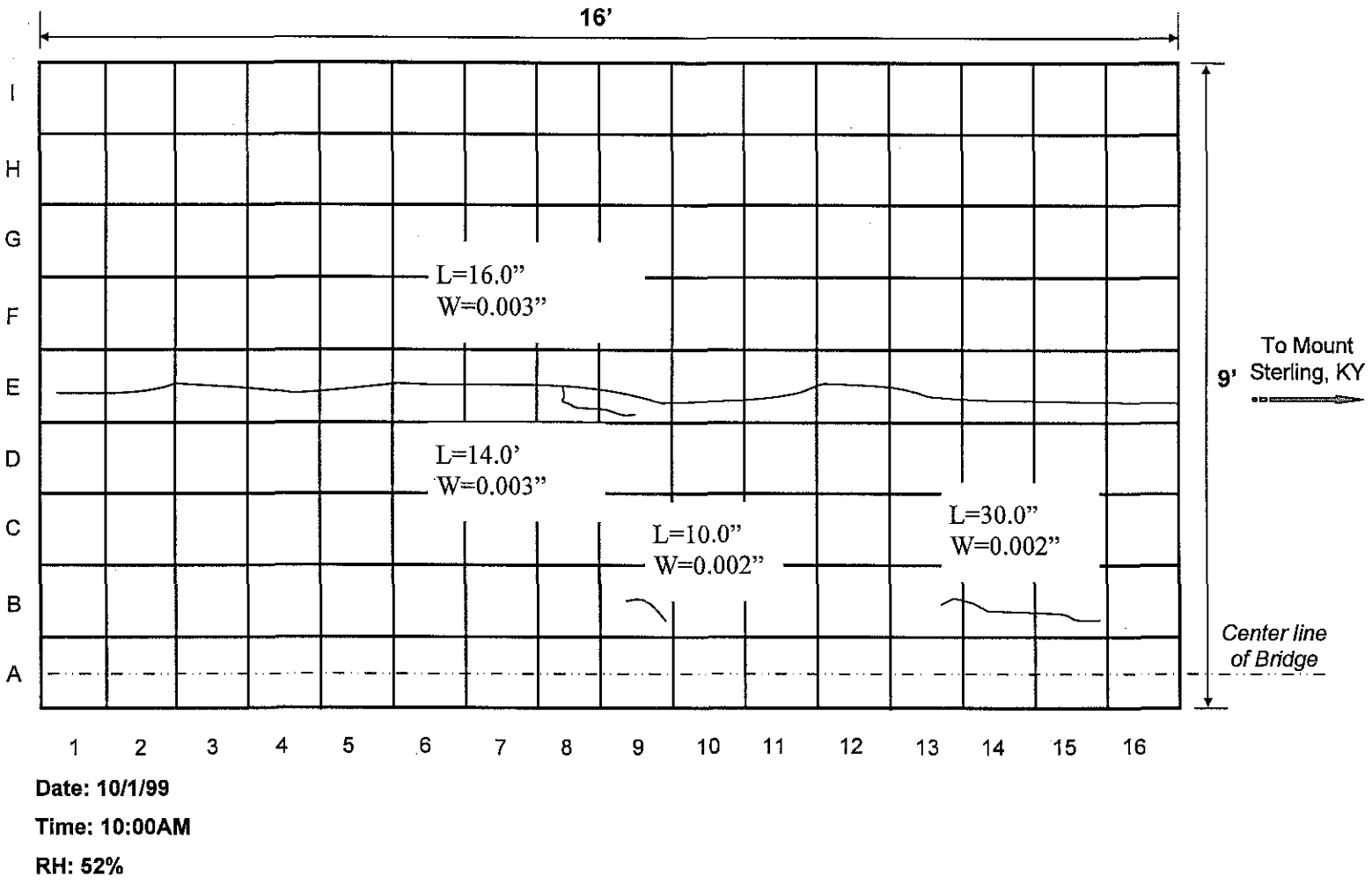

Fig. A40. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

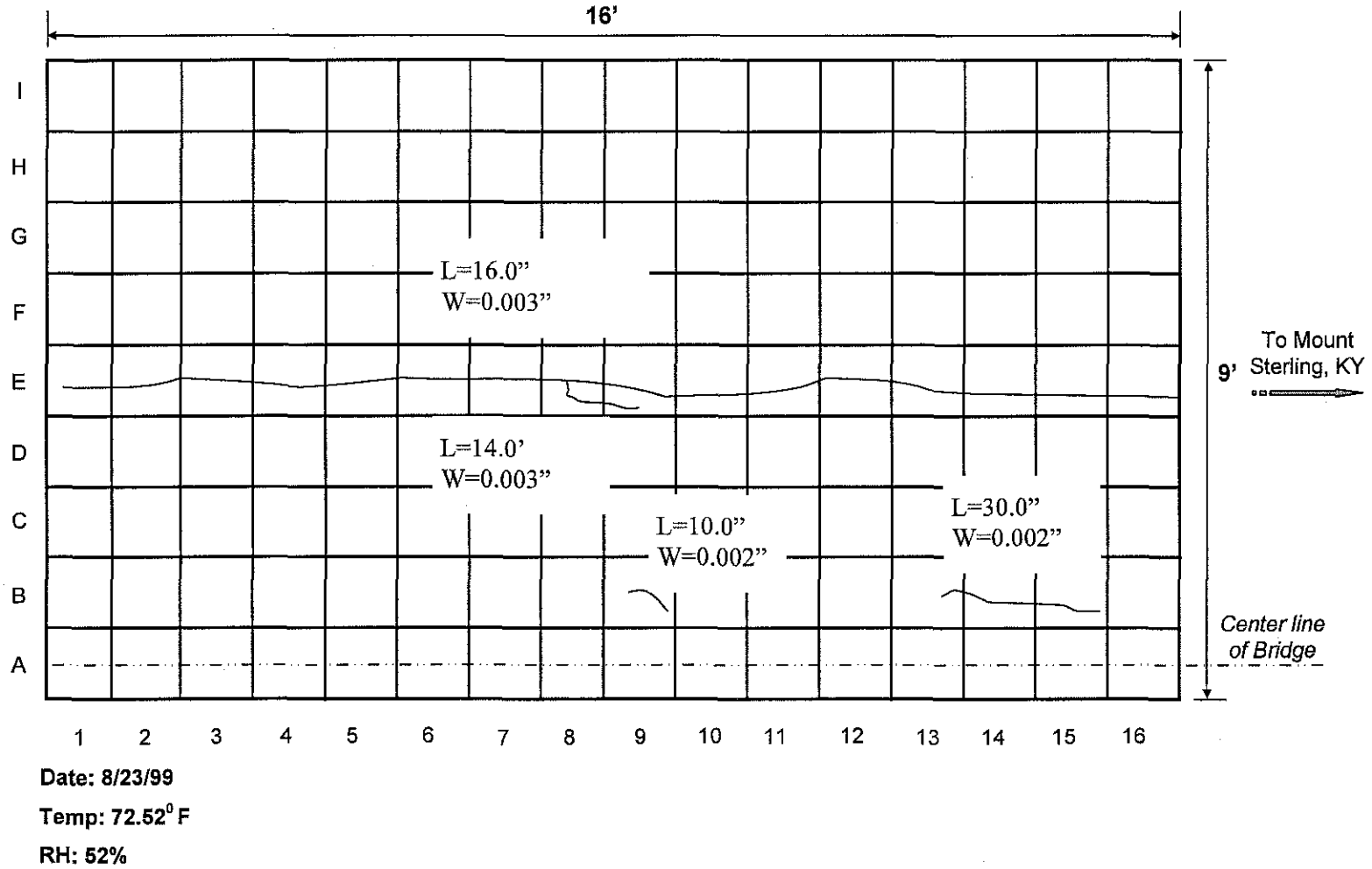

Fig. A41. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

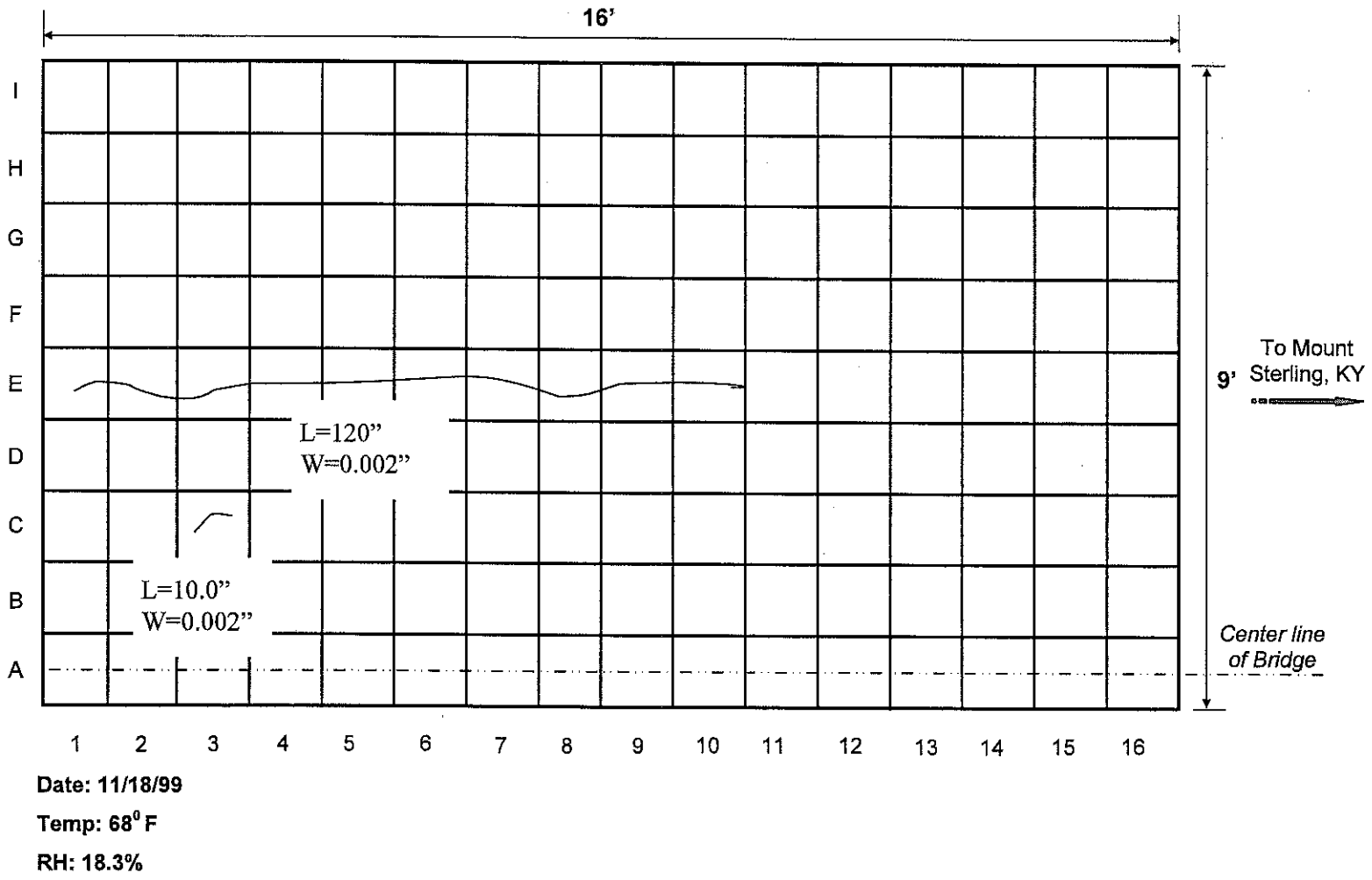

Fig. A42. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

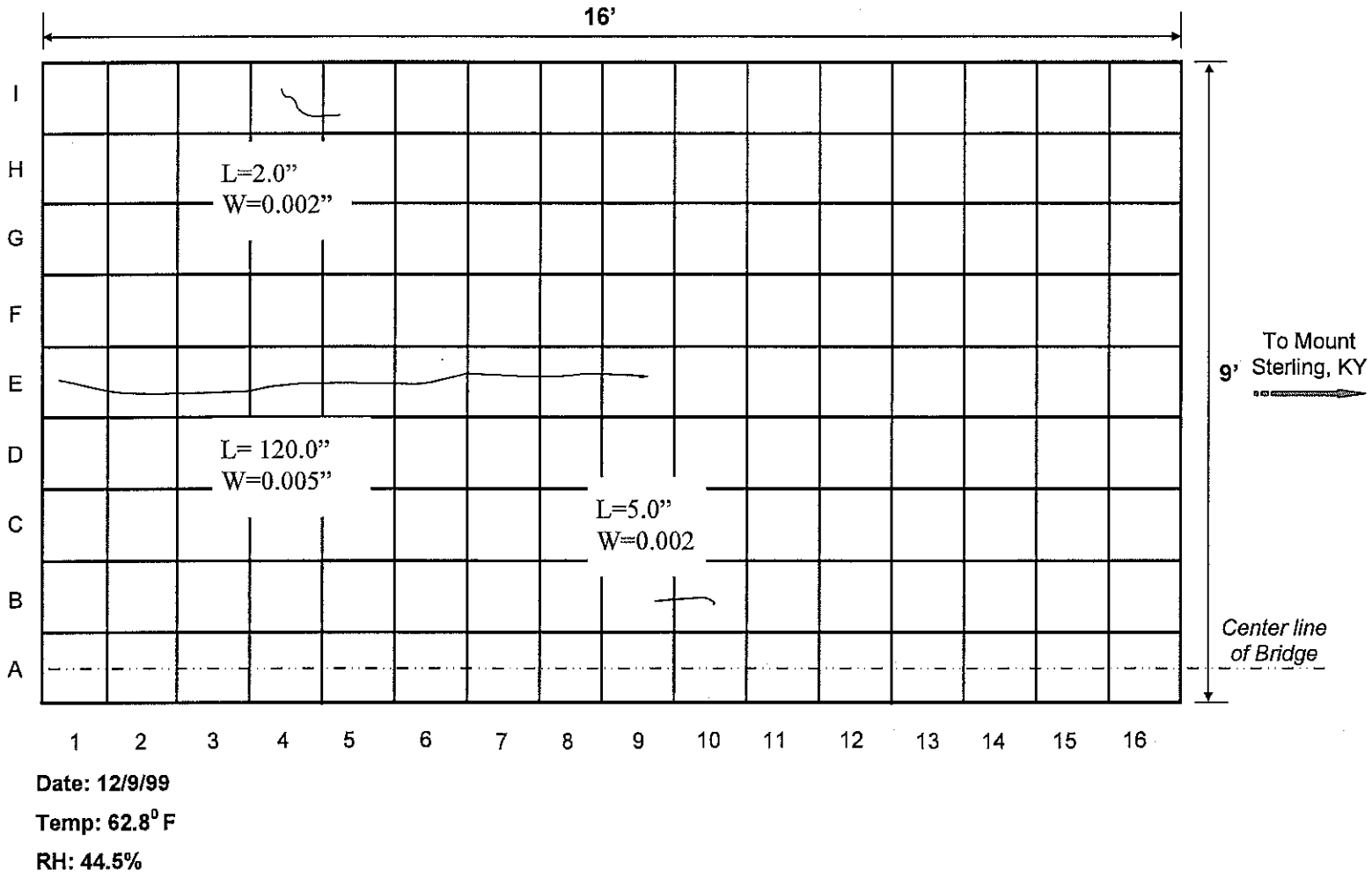

Fig. A43. Cracks observed in the top surface of the bridge deck in the GFRP area under unloaded condition

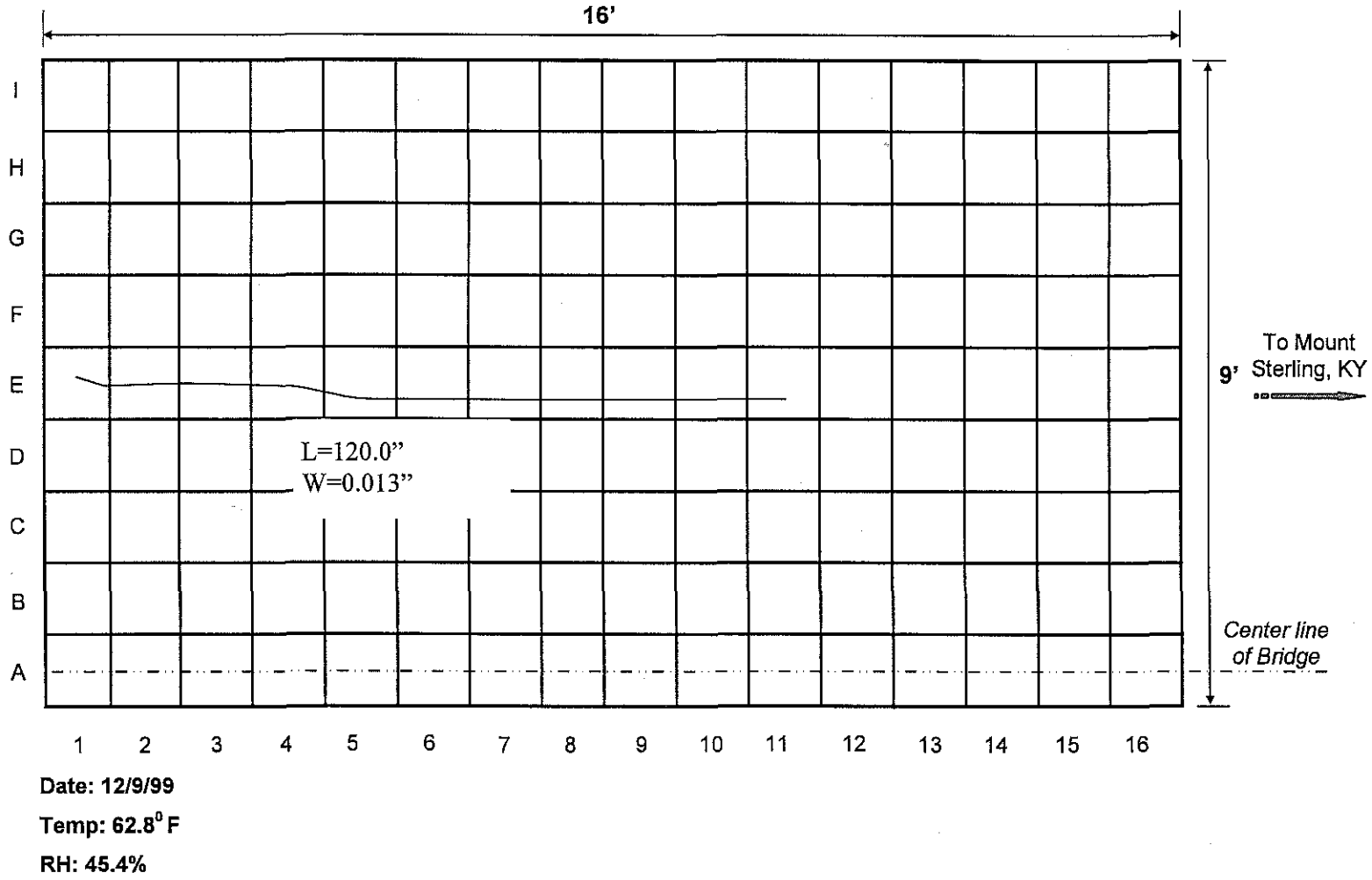

Fig. A44. Cracks observed in the top surface of the bridge deck in the GFRP area under loaded condition

Appendix B

Cracks Observed in the CFRP Reinforced Area

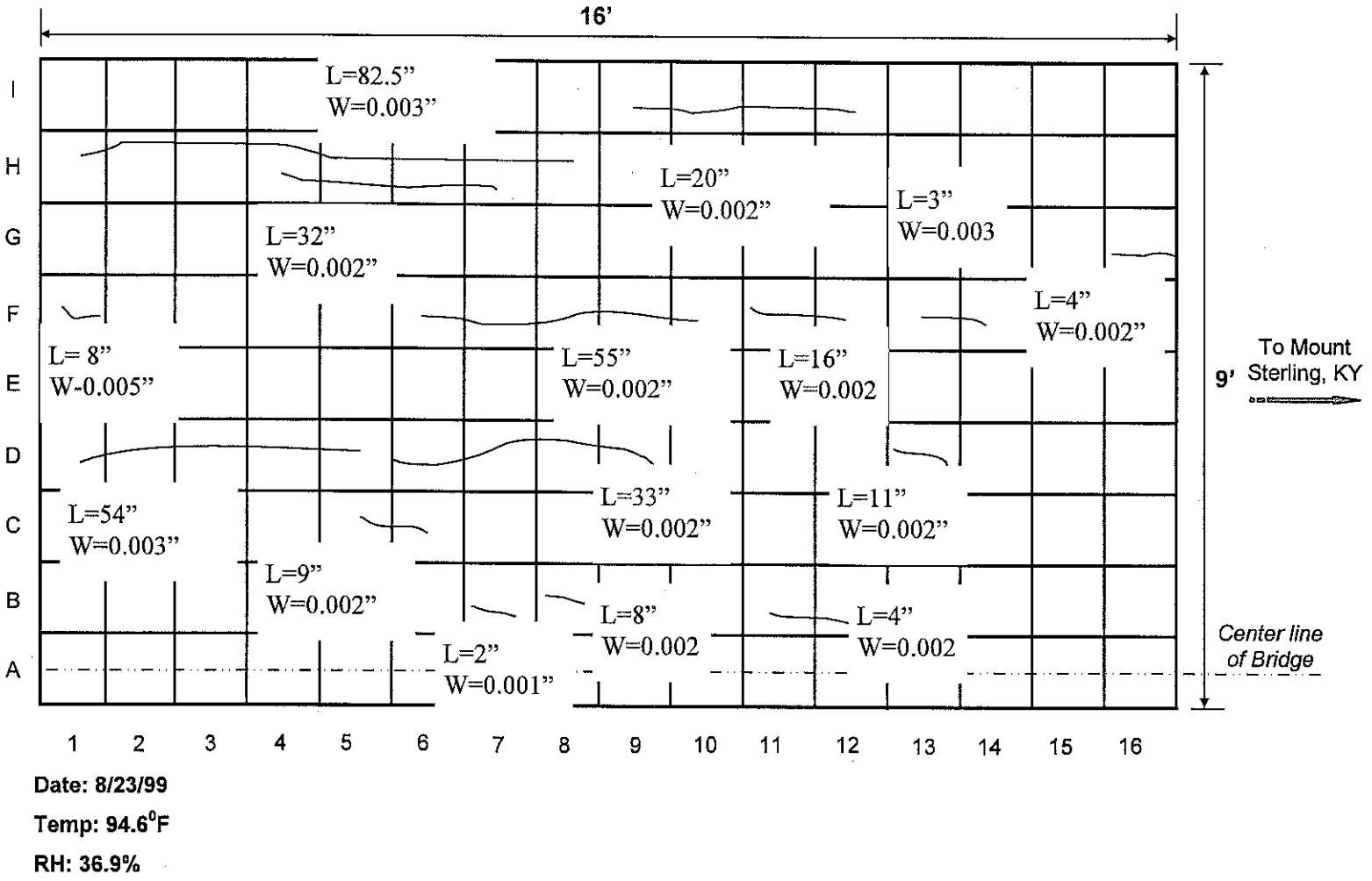

Fig. B1. Cracks observed in the top surface of the bridge deck in the steel area under unloaded conditions

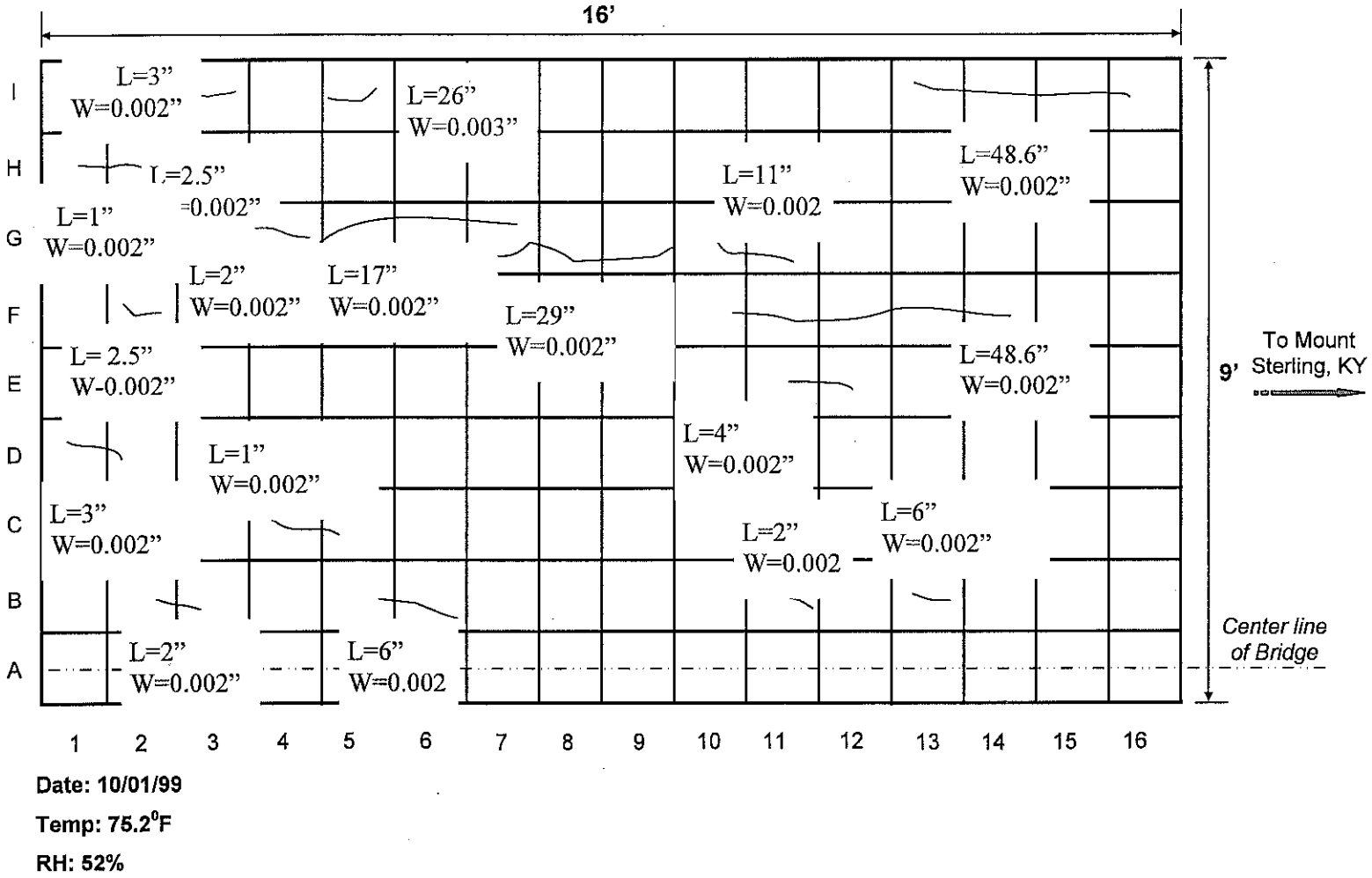

Fig. B2. Cracks observed in the top surface of the bridge deck in the steel area under unloaded conditions

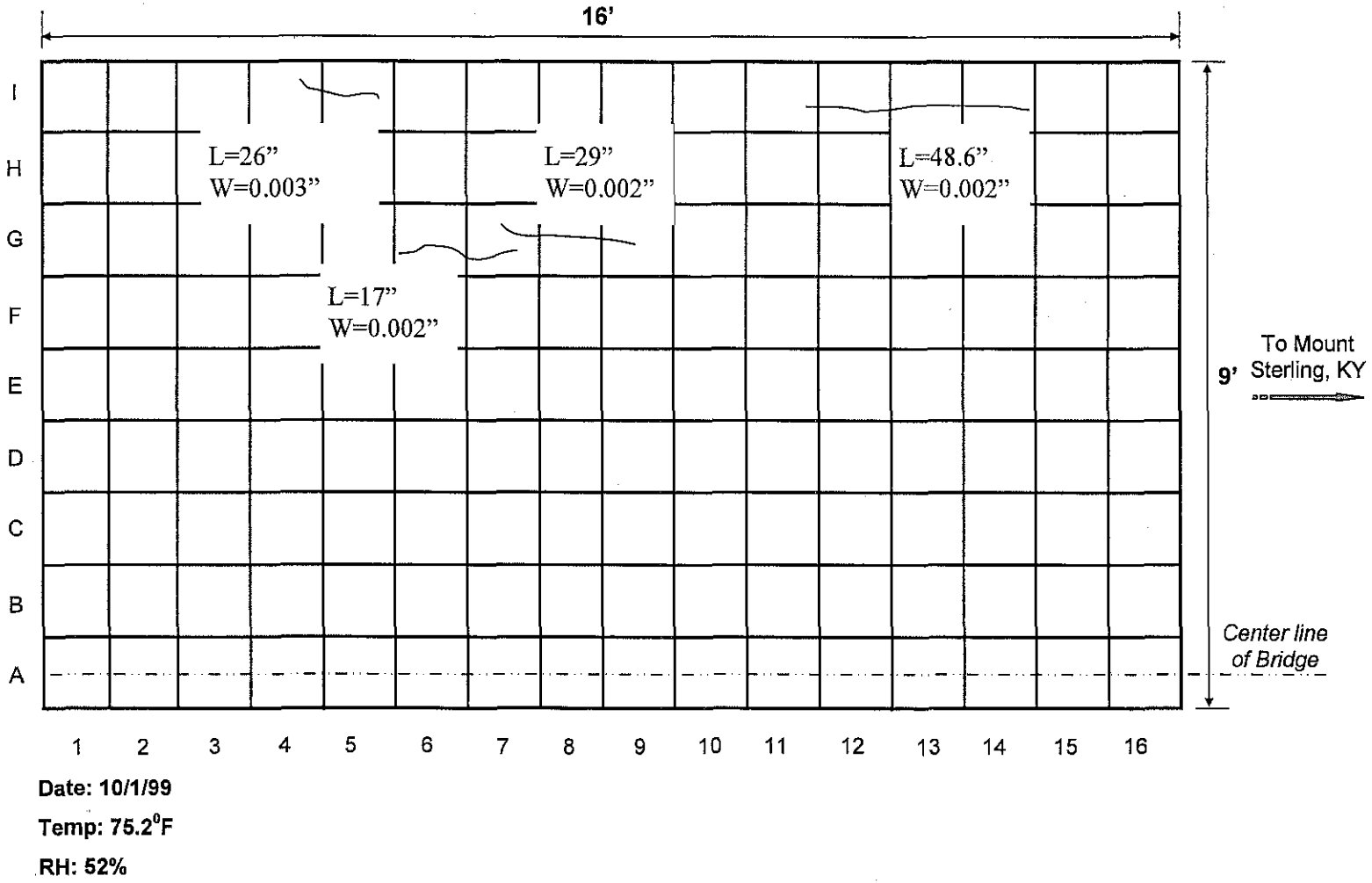

Fig. B.3 Cracks observed in the top surface of the bridge deck in the steel area under loaded conditions

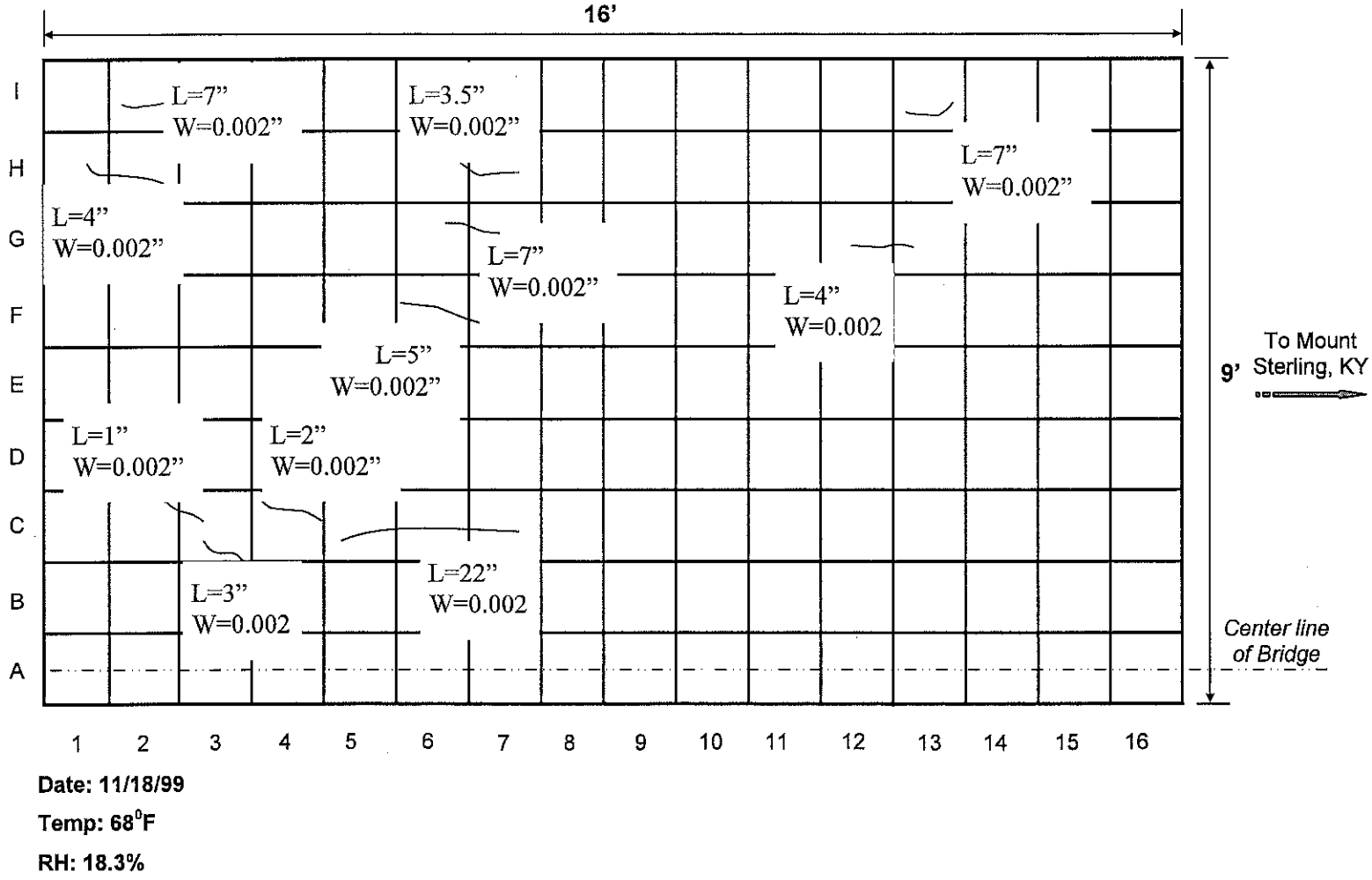

Fig. B4. Cracks observed in the top surface of the bridge deck in the steel area under unloaded conditions

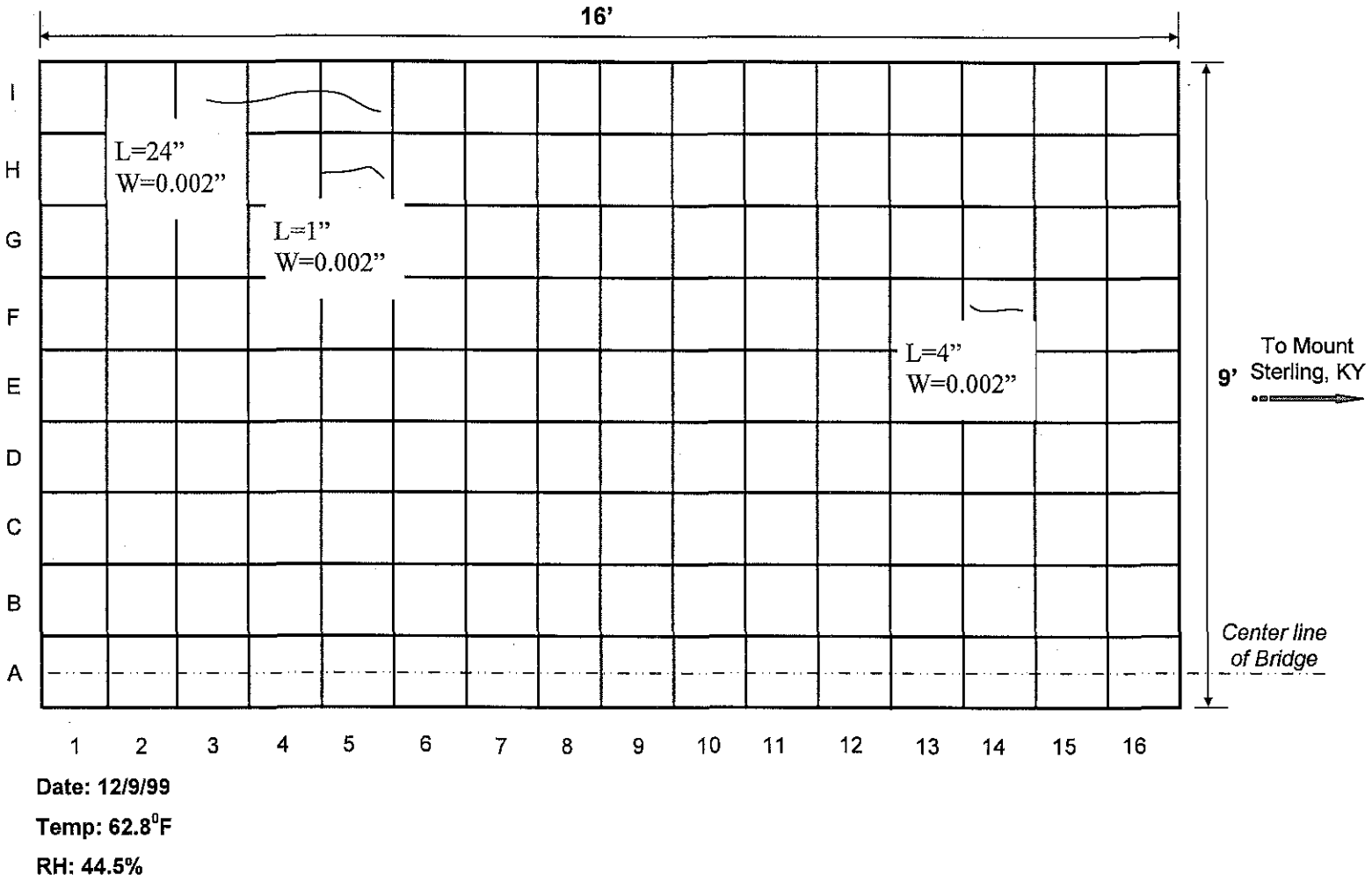

Fig. B5. Cracks observed in the top surface of the bridge deck in the steel area under unloaded conditions

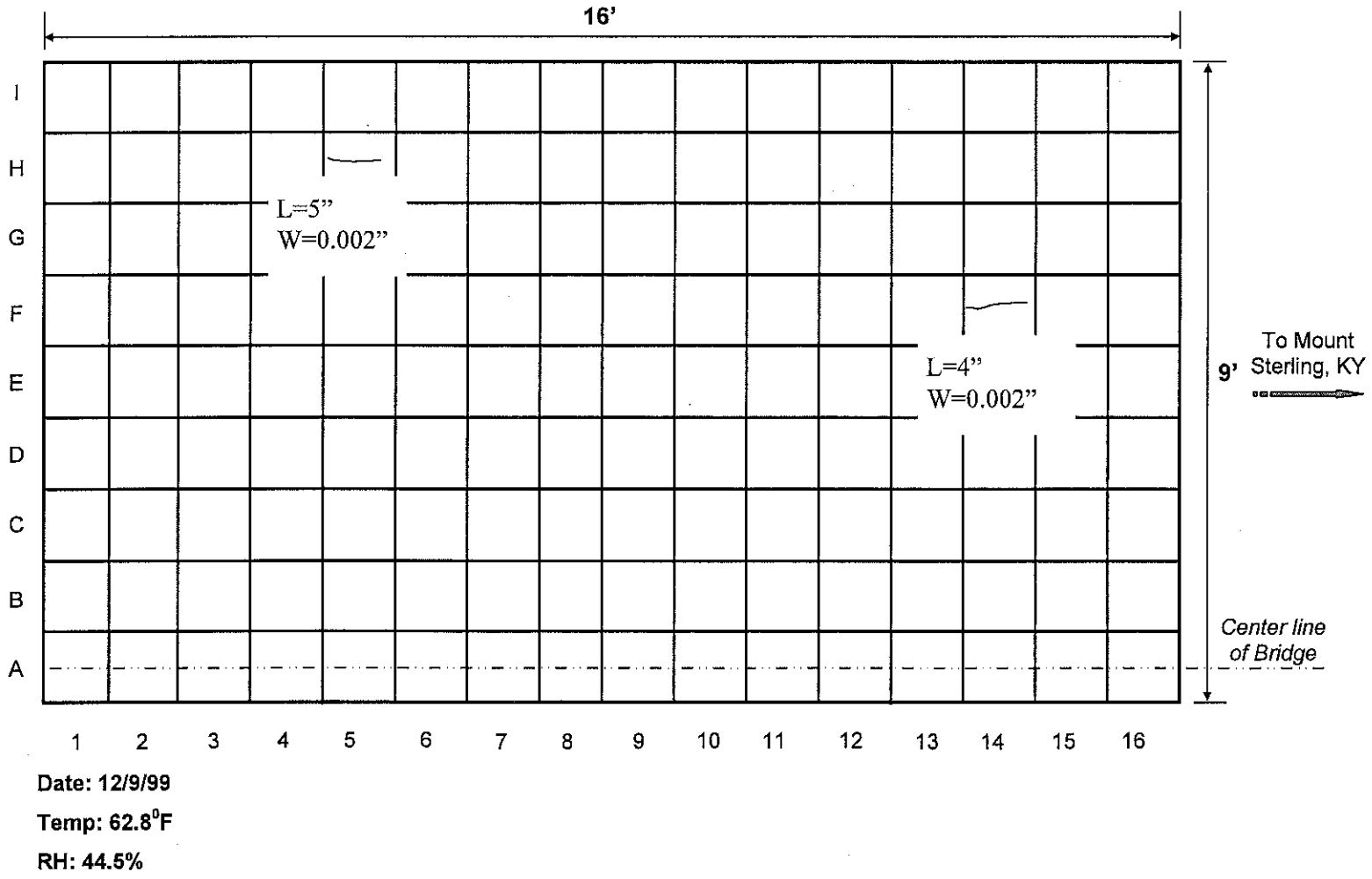

Fig. B6. Cracks observed in the top surface of the bridge deck in the steel area under loaded conditions

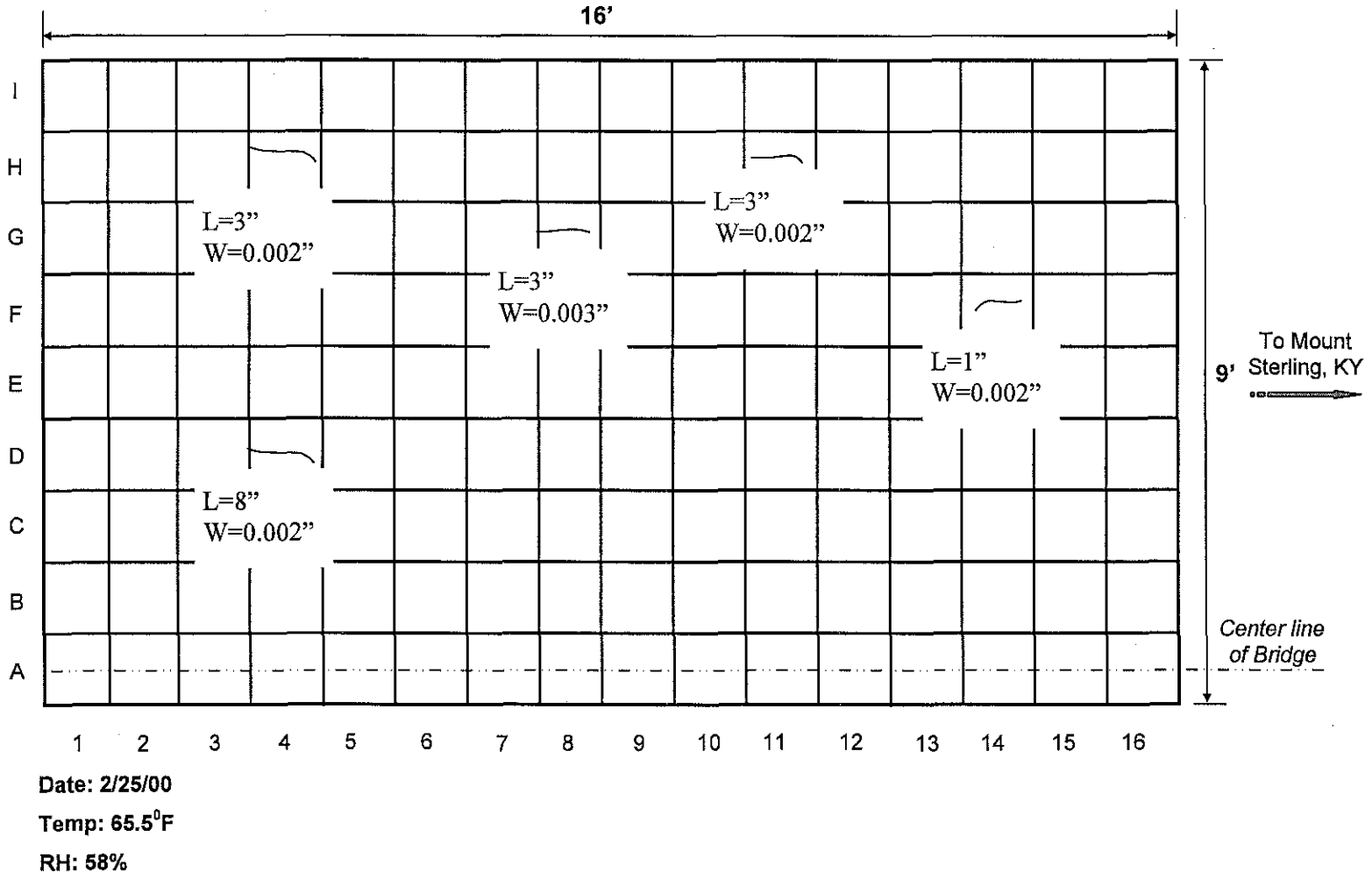

Fig. B7. Cracks observed in the top surface of the bridge deck in the steel area under unloaded conditions

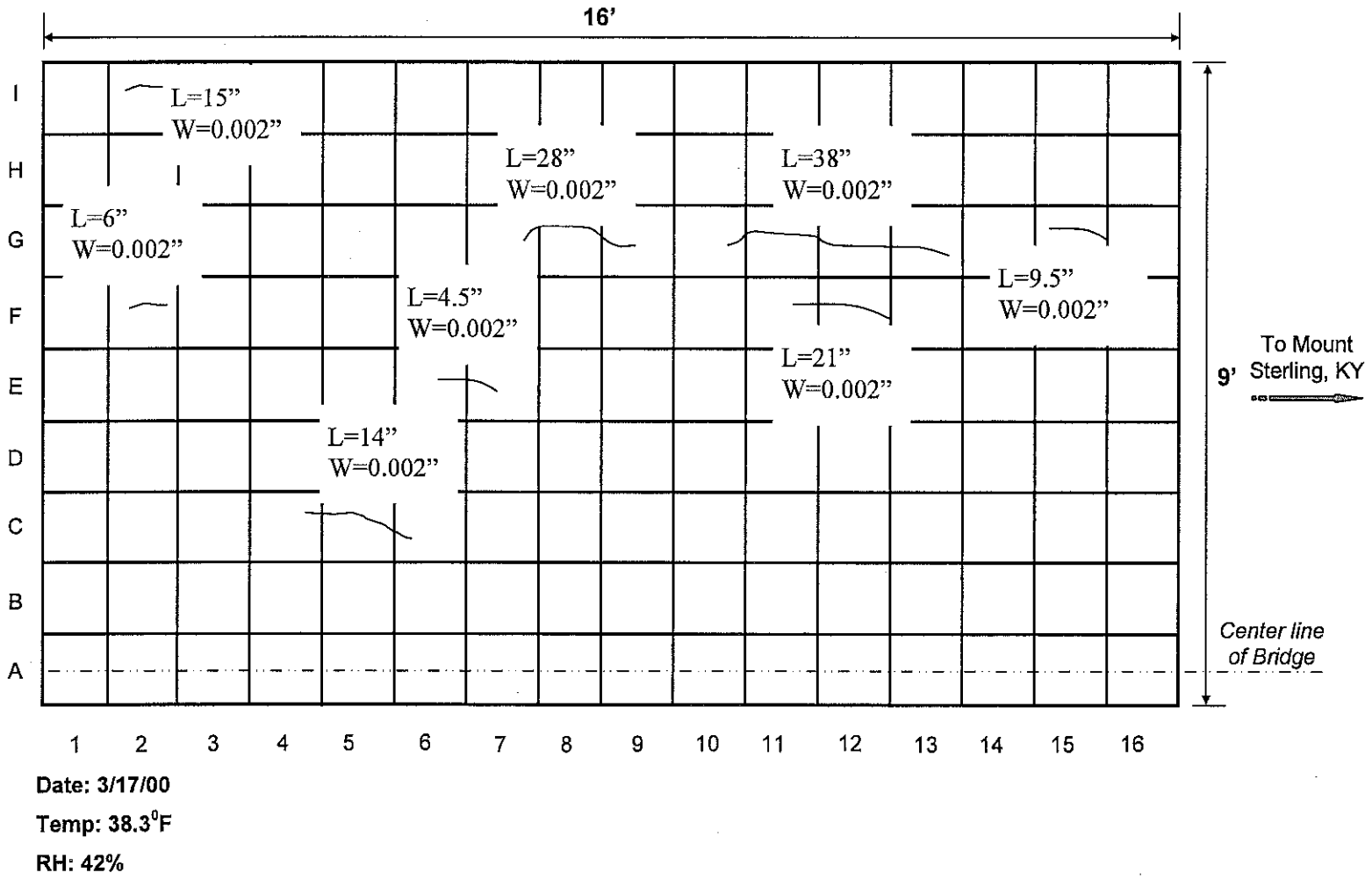

Fig. B8. Cracks observed in the top surface of the bridge deck in the steel area under unloaded conditions

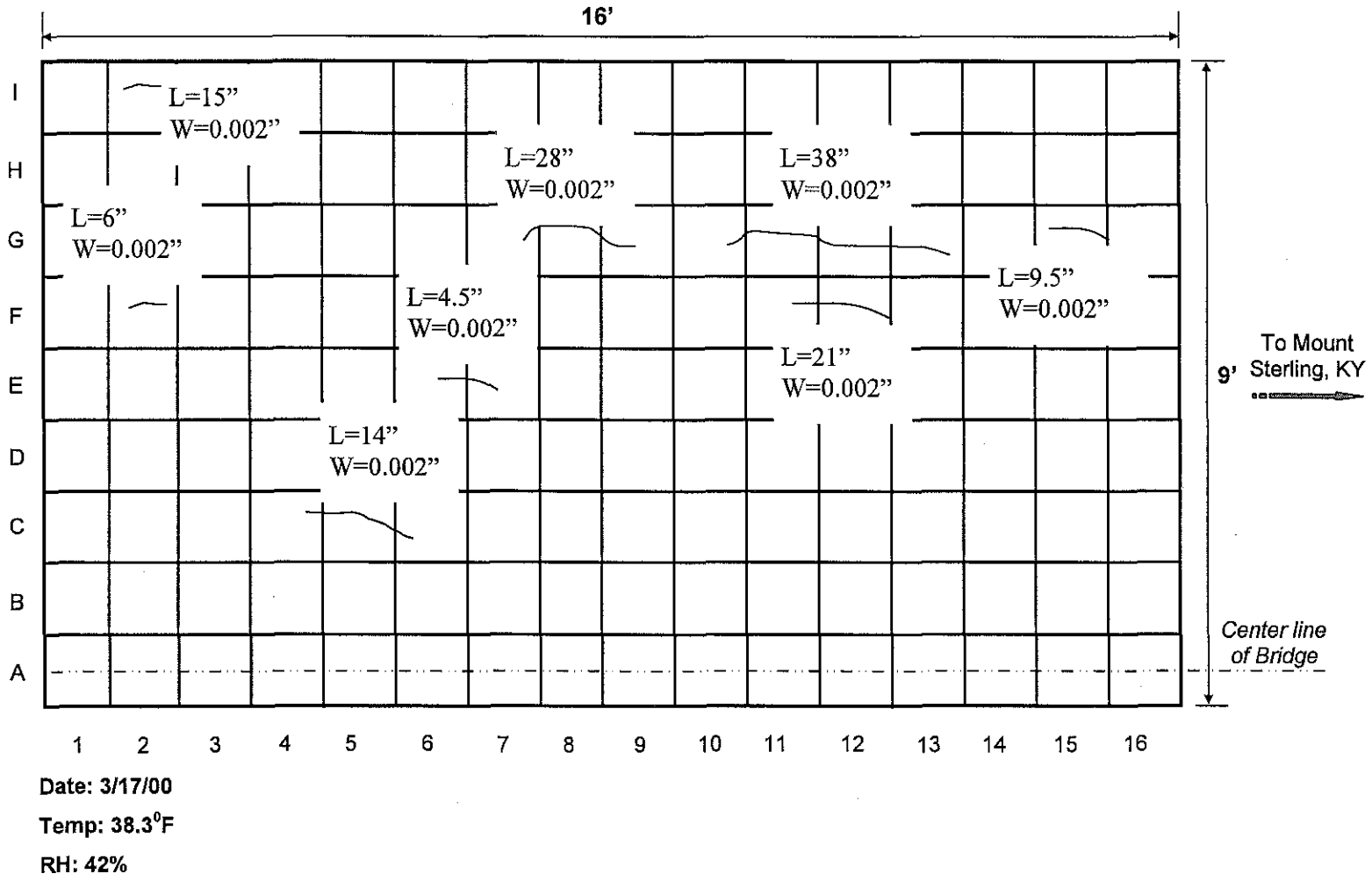

Fig. B9. Cracks observed in the top surface of the bridge deck in the steel area under loaded conditions

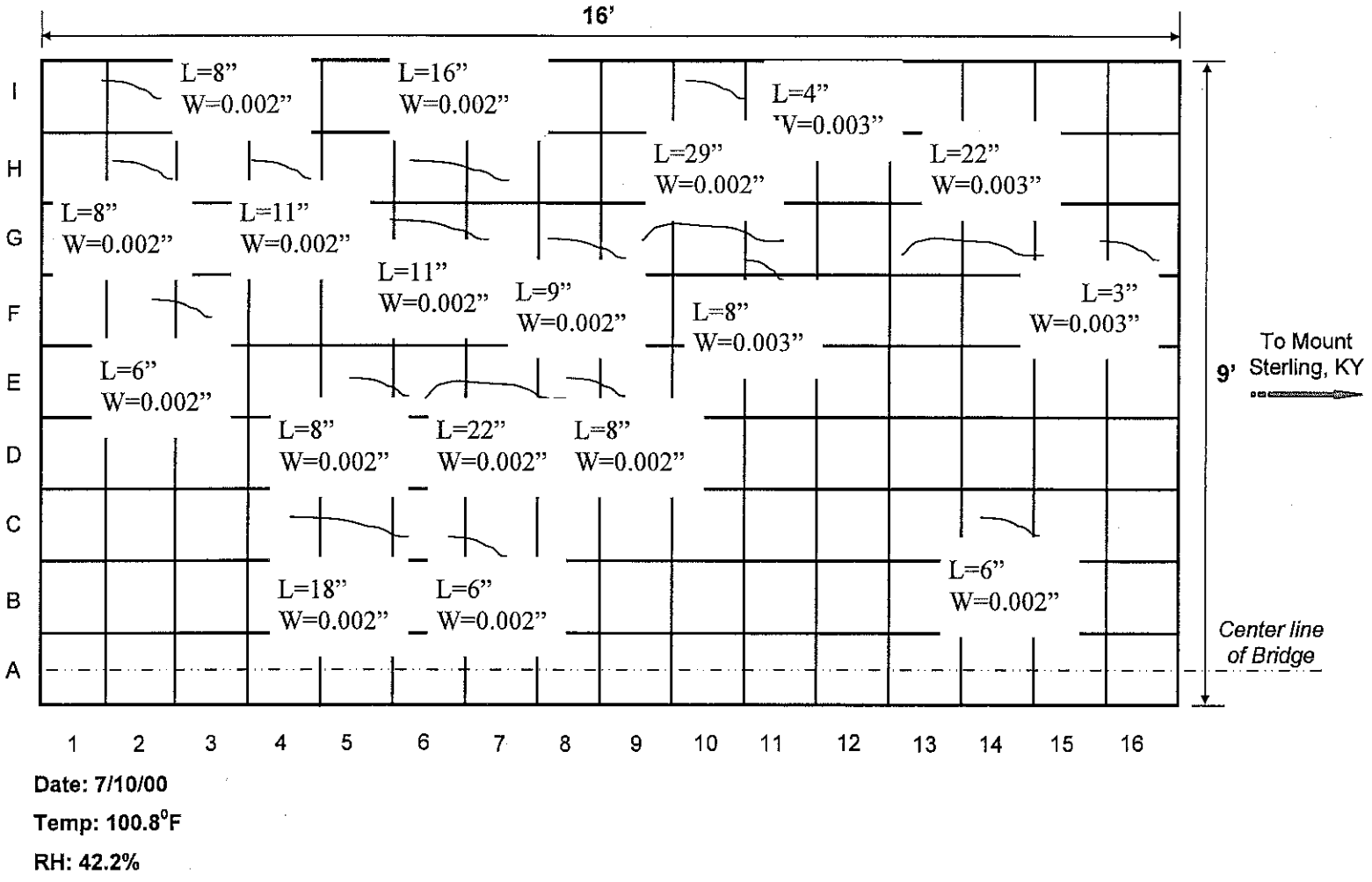

Fig. B10. Cracks observed in the top surface of the bridge deck in the steel area under unloaded conditions