Critical assessment of evidence related to the 1989 Hillsborough Stadium disaster, UK

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The Hillsborough Stadium disaster that unfolded on the Leppings Lane terrace of Sheffield Wednesday Football Club's ground in Sheffield, UK, on 15 April 1989 resulted in 96 fatalities. Evidence presented to the initial 1989 inquiry, the 1991 civil court case and the 2016 inquest is critically assessed, together with additional relevant research findings. The matters discussed are concerned with fundamental technical principles that provide for spectator safety on terraces such as that on which the disaster unfolded. This paper examines the significance as to the lack of compliance with the applicable guidance. The terrace barrier testing undertaken prior to the disaster is examined and considered inadequate.

Notation

P_1	force related to a compliant barrier height
P_2	force related to a non-compliant barrier height
P_o	force generated by an individual spectator leaning on level ground: kN
P_{slope}	force contributed by an individual spectator leaning on the terrace: kN
α	inclination of the terrace

1. Introduction

The Hillsborough Stadium disaster on 15 April 1989, which resulted in the deaths of 96 persons, has been exhaustively examined. The documentation from which the Hillsborough Independent Panel (2012) Report derives is extensive. Forthcoming legal proceedings that will follow the recent inquest (2016) concern criminal prosecutions relating to procedural and legislative matters. The content that follows does not relate to those proceedings as it is concerned solely with technical matters relating to the terrace on which the fatalities occurred and how those technical matters were examined during the Taylor inquiry (1989) and the recent inquest (2016).

The Wheatley inquiry (Home Office, 1972) into crowd safety at sports grounds prompted the publication of the *Guide to Safety at Sports Grounds* (Home Office, 1976), commonly referred to as the Green Guide. The second edition (Home Office, 1986: p. 7) of the Green Guide would have been the relevant edition at the time of the Hillsborough disaster and stated the following

The Guide is an aid to, not a substitute for, professional judgement and common sense.

Lord Justice Taylor's inquiry immediately following the disaster provided an interim report (Home Office, 1989) and a final report (Home Office, 1992).

The inquest (2016) heard evidence considered by the Taylor inquiry together with additional evidence. The inquest jury returned a verdict that those who died in the disaster were

unlawfully killed. In addition, the jury also considered that there were features in the design, construction and layout of the stadium that were dangerous and/or defective that caused and contributed to the disaster. The jury's explanation for this consideration included the statement that the design and layout of the crush barriers in pens 3 and 4 were not fully compliant with the Green Guide.

The disregard of established technical guidance concerning the provision of spectator safety on viewing terraces was clearly evident prior to the disaster. The design of the terrace and the barriers in place on the day of the disaster demonstrates poor professional judgement. Crowd management decisions on the day of the disaster, while not examined here, are considered to have been an initiating event as opposed to the immediate cause.

The commentary that follows critically examines the evidence presented to the Taylor inquiry (Home Office, 1989) and the most recent inquest (Hillsborough Inquests, 2016). The inadequacy of the barrier testing prior to the disaster is clearly demonstrated. A research study (Evans and Hayden, 1971) was discussed during the Hillsborough inquests that related to Dr Eastwood's justification for a non-compliant barrier having a height lower than the guidance provided in the Green Guide (Home Office, 1986). Dr Eastwood was Sheffield Wednesday Football Club's (SWFC) consultant structural engineer providing advice on structural and safety matters. During the Hillsborough Inquests (2016), discussions took place between Mr Beer and Mr Cutlack and between Ms Lambert and Mr Cutlack concerning barrier height. Mr Cutlack was the engineer instructed by the coroner to provide the jury with independent expert advice. Mr Beer QC appeared on behalf of SWFC, and Ms Lambert QC was a counsel to the inquest asking questions on behalf of the coroner. The discussions demonstrated that counsels' and the expert's understanding as to the consequence of a non-compliant barrier was only partially understood.

2. The terrace

The fatalities occurred on the terracing illustrated in Figure 1. The terrace incline was 14°. The majority of fatalities occurred in

Figure 1. Pens 3 and 4, Leppings Lane terrace (adapted from Home Office (1989))

pen 3 where the two right-hand sections of barrier 124a, as viewed from the pitch side in Figure 2(b), collapsed due to crowd pressure. Spectator ingress to the terracing was through the tunnel at the rear, evident in Figure 1.

Table 1 provides individual barrier heights and lengths for pens 3 and 4; see Figure 2(b).

Barrier compliance required a height within the range of 1.02–1.12 m, with the preferred height being 1.1 m. In pen 3, the total length of compliant barriers was 21 355 mm. In pen 4, the total length of compliant barriers was 29 875 mm.

Table 1. Barrier lengths and heights (Ralph Brade & Associates, 1989)

Pen 3			Pen 4		
Barrier	Length: mm	Height: m	Barrier	Length: mm	Height: m
149	7005	1.10–1.13	150	6040	1.12–1.14
136	5475	0.83–0.86	144	2425	1.08–1.10
136a	4525	0.85–0.87	137	4460	0.89–0.91
124a	7425	0.95–1.00	138	3645	0.89–0.91
125	5395	0.92–0.94	132	4495	1.12–1.14
Fence	14 350		125	1850	0.92–0.96
			127	2310	0.95–0.98
			128	6880	0.92–0.99
			126	2270	1.14–1.15
			Fence	14 645	

Three rows of barriers each having two gaps, >1.1 and <1.4, and within the specified height range would have provided compliance with the Green Guide (Home Office, 1986). Using the maximum gap width, the total barrier lengths necessary to achieve 100% compliance are provided in Table 2 and are compared with the provision immediately prior to the disaster.

Fatalities in pen 3 greatly exceeded those in pen 4.

(a)

(b)

Figure 2. (a) Typical structural form of barriers, old, repaired and new; (b) barrier layout where the disaster unfolded. ↓, spectator ingress

Table 2. Barrier provision

	Compliance requirement	In situ 1989	%
Pen 3	49 000 mm	21 355 mm	44
Pen 4	50 180 mm	29 875 mm	59

Norton (1989) provides the average packing densities of people in pens 3 and 4, as indicated in Figure 2(b), using head counts from photographs taken shortly after 15.00 h. The crush barriers were adopted to define the row boundaries. A head count using photographic evidence was considered appropriate for calculating the population of rows 2, 3 and 4. Identification of heads in row 1 was less certain. Tests undertaken on level ground by the Health and Safety Executive (HSE) (Nicholson, 1989), indicated that a packing density of 10 persons/m² could be achieved without distress. Norton (1989) considered that the numbers in row 1 estimated using this value would be neither unrealistically high nor unrealistically low. It was further considered that there was no distinct bias to suggest an appreciable difference between the crowd packing densities in pens 3 and 4. The Green Guide (Home Office, 1986) would have allowed for the capacity of each pen to be derived using a packing density of 5.4 persons/m² had the barrier geometry complied.

3. The inquiry by the Rt Hon Lord Justice Taylor

Two reports (Home Office, 1989, 1992) were presented to Parliament. The interim report (Home Office, 1989: p. 41–42, paragraphs 237 and 238) briefly considered the testing of barriers and stated

Dr Eastwood and his staff had undertaken the periodical testing of crush barriers required by the Green Guide and the Safety Certificate. Barrier 124a had been tested in July 1988 and passed.

The test had been carried out in accordance with Dr Eastwood’s interpretation of Annex C to the Green Guide. That requires an evenly distributed force of 6 kN/metre width to be applied for 3 five-minute periods, the interval between applications to be as short as possible. A record has to be kept of the amount of deformation during each loading and the percentage recovery. If the recovery is less than 50% after the third application of load, there must be a retest. The question is 50% or 75% of what? Is the recovery to be in relation to the position of the barrier before the first application of force or before the third?

Dr Eastwood adopted the position prior to the second loading cycle as being applicable. Lord Justice Taylor considered advisement from Professor Maunder, assessor to the inquiry, that the recovery should be by reference to the position of the barrier before the first application of load. However, Lord Justice Taylor held Eastwood’s interpretation to be tenable on the grounds of Green Guide ambiguity.

The transcript of Lord Justice Taylor’s inquiry for 26 June afternoon session (1989) provides a question put by Lord Taylor to Mr A. Toulson, who appeared on behalf of Dr Eastwood.

I don’t think anybody has attacked the method of testing, have they?

Mr A. Toulson answered no.

As subsequently demonstrated, it is difficult to understand why this line of questioning was not pursued.

With reference to barrier testing, on 10 July 1989 Professor Maunder wrote to Mr A. R. Whalley, secretary to the Hillsborough inquiry

His (Dr Eastwood’s) approach to the measurement of deflections is not satisfactory; ... Although a crush barrier may appear to be a simple structure, the distribution of load through its component parts is far from simple. The neglect of comprehensive measurements of deflection under load makes the interpretation of results uncertain.

The need for comprehensive deflection data, as described by Maunder (1989), was eventually recognised in the fourth edition of the Green Guide (Home Office, 1997).

Annex C of the applicable Green Guide (Home Office, 1986) concerns barrier testing. Three applications of load were required with pass or fail criteria relating to barrier recovery.

Dr Eastwood’s description relating to the first cycle is provided in the transcript of the inquest (Hillsborough Inquests, 2016) as taken from the transcript of the Taylor inquiry (Home Office, 1989: p. 119).

I have always regarded it as standard practice when testing structures in which there is soil/structure interaction, or where the carrying capacity of the structure is determined by plastic hinge mechanism, for ‘bedding-in’ loads to be applied before the test proper begins. Hence the deflections in the first cycle of loading are ignored.

The term ‘bedding-in’ was not in the 1986 edition of the Green Guide. The object of applying bedding-in loads is to settle the structure under investigation and associated measuring devices – that is displacement transducers and the like. A bedding-in load should be sufficient to deform the structure and be less than the intended future loading.

Professor Maunder (10 July 1989) relayed, in a letter to Andrew Collins QC, that he had been orally informed by the Home Office as follows.

Cyclical loading was intended to simulate the action of successive surges.

Figure 3 and the related Figure 4 illustrate deflection characteristics for a barrier subjected to load.

Figure 3. Force–deflection characteristic for a structure subjected to loading

In Figure 4(a), O–A1, following release of the load, would include a bedding-in element. In Figure 4(b), O–A2, following release of the load, would include a bedding-in element and a plastic deformation; the applied loading lies between points B and C in Figure 3. In order to ascertain the separate contributions from bedding-in and plasticity, deflections obtained during incremental loading would be required. The issue was recognised following the Hillsborough disaster in the third edition of the Green Guide to safety at sports grounds (Home Office, 1990) with a two-part test requirement as follows

- part 1: bedding-in cycle with the barrier being loaded up to its design service load
- part 2: two further loading cycles up to the proof load ($1.2 \times$ design service load).

The two-part barrier test method replaced the three-cycle test in the 1986 edition of the Green Guide, the interpretation of which Lord Justice Taylor determined to be ambiguous.

Figure 4. (a) Force–deflection characteristic with no plasticity; (b) force–deflection characteristic with plasticity occurring. O–A1, deflection attributable to bedding-in; O–A2, deflection attributable to bedding-in and plasticity

The barrier test data available to the Taylor inquiry (Home Office, 1989) provided no detail regarding incremental loading.

Professor Maunder's note (24 July 1989), referred to earlier, stated that

the neglect of comprehensive measurements of deflection under load makes the interpretation of results uncertain.

Figure 5 schematically illustrates the nature of the Eastwood & Partners test procedure for a three-bay barrier. A three-bay barrier necessitated two consecutive tests for each of three loading cycles. The first test employed four-point loading applied to each of bays 1–2 and 2–3 as illustrated in Figure 5. Measurement of deflection was taken at only one location, the midpoint of bay 1–2. The second test involved applying four-point loading to each of bays 2–3 and 3–4 while recording deflection at the midpoint of bay 2–3. The lack of deflection measurements relating to supports creates the uncertainty as to the integrity of a barrier as noted earlier by Maunder (24 July 1989).

The Eastwood & Partners test procedure for a two-bay barrier required a single test incorporating three loading cycles with only a deflection at the midpoint of bay 1–2 being recorded.

Historical data were provided to the Taylor inquiry (Home Office, 1989) concerning barrier testing undertaken by Eastwood & Partners prior to the disaster and included the following.

- 1983: Test data indicate that the integrity of barrier 124A, which failed on the occasion of the disaster, was suspect.
- 1985: In five instances, the stanchions of various barriers failed to sustain the test load.
- 1988: Test data again indicate that barrier 124A was suspect.

Figure 5. Three-bay test, 1986. Location of measured deflection.
△, measured deflection

Eastwood & Partners undertook remedial work in accordance with their interpretation of barrier test data.

4. Barrier testing following the disaster

Figure 2(a) illustrates the nature of barriers on the Hillsborough terraces at the time of the disaster. Barrier testing undertaken by Dr Eastwood and others in 1990 was more comprehensive than testing prior to the disaster. The barriers tested were all two-bay barriers of the older type in pens 2 and 5. Pens 2 and 5 were immediately adjacent to pens 3 and 4, respectively; the barriers were of a similar construction to barrier 124a. Figure 6 schematically illustrates a two-bay barrier and the locations at which deflections were recorded. The locations coincided with Maunder's description relating to significant deflections.

In all tests, a loading cycle composed of five increments with the maximum load being maintained for 5 min before unloading. A number of barriers failed during the 1990 tests.

Barrier 123 was a two-bay barrier in pen 2, similarly constructed to barriers in the adjacent pen 3. Barrier 123 had previously been passed by Eastwood & Partners (1983, 1988). During the 1990 tests, failure, as in collapse, occurred during load cycle 1.

Comparative test deflections (in millimetres) at b for barrier 123 (see Figure 6) are presented in Table 3.

For load cycle 1, the barrier failed, as in collapse, during the required sustained application, for a 5 min interval, of the proof

Figure 6. Two-bay test, 1990. Locations of measured deflections

Table 3. Comparative test deflections (in millimetres) at b for barrier 123

	Load cycle 1	Load cycle 2	Load cycle 3
1983	18.5	16.5	16.5
1988	19	19	21
Test undertaken following the disaster			
1990	25		

load of 6 kN/m. The deflection of 25 mm was measured at the start of the 5 min interval.

Barrier 141 was a two-bay barrier in pen 5, similarly constructed to barriers in the adjacent pen 4, tested and passed by Eastwood & Partners (1983, 1988).

- 1983: Barrier 141 failed during load cycle 1; the barrier was repaired.
- 1988: Barrier 141 passed with 90% recovery and a maximum rail deflection of 22 mm during load cycle 1. The deflections recorded during load cycles 2 and 3, both 20 mm, showed 100% recovery.

In the test undertaken following the disaster, in 1990, barrier 141 rail recovery during load cycle 2 was 60%, requiring a retest. The barrier failed during load cycle 1 of the retest.

During the Taylor inquiry (Home Office, 1989: p. 107), Mr Collins, appearing on behalf of the inquiry, put the following question to Dr Eastwood.

But surely you are concerned with the integrity of the whole construction which includes the stanchion as well as the horizontals?

To which Dr Eastwood replied

The stanchion has had the load on it and gets it fully when the two bars either side are there. The deflection which we measure is that of the horizontal bar because that is what dominates. The amount of movement in these stanchions is very, very tiny.

Deflections recorded for two-bay barrier 123 when tested in 1990 are provided in Table 4.

During cycle 1, the proof load of 6 kN/m was maintained as required. The centre support, stanchion 2, failed within the 5 min interval.

Four two-bay barriers failed during the 1990 tests. In each case, the central stanchion failed under the following loadings

Table 4. Barrier 123 test – 1990 (see Figure 6) post Hillsborough disaster

kN/m	Deflections: mm				
	a (stanchion)	b (rail)	c (stanchion)	d (rail)	e (stanchion)
0	0	0	0	0	0
1.22	1.00	8.05	3.60	7.00	1.00
2.44	2.55	11.10	4.25	10.60	1.40
3.65	2.18	14.00	6.25	14.90	2.00
4.87	2.70	16.70	8.15	17.00	2.60
6.13	3.30	25.00	17.80	Gauge moved	3.40

- barrier 123: 6.0 kN/m
- barrier 124: 7.1 kN/m
- barrier 128A: 7.1 kN/m
- barrier 141: 6.0 kN/m.

The results obtained from the barrier tests undertaken following the disaster added emphasis to Professor Maunder's comments regarding the need for comprehensive deflection data.

Additional testing subsequent to the disaster established horizontal failure loads for the stanchion supports of the barrier rail. Five stanchions were independently subjected to a horizontal point load at rail height. The failure loads were 17.5 ± 2.5 kN.

Failure appeared to be caused by ductile failure at the top of the rear leg.

The Third Party claimant in civil proceedings in the Liverpool High Court (1989) in the matter of the disaster at Hillsborough stadium 15th April 1989 was the Chief Constable of South Yorkshire Police. The first Third Party Defendant was Sheffield Wednesday Football Club who employed Sir William Halcrow and Partners Ltd to provide an expert opinion in support of their defence. Halcrow (1990: p. 5) provided their opinion as to the failure load of Barrier 124A.

Halcrow consider that the barrier 124A collapsed at or about 6 kN/m.

Halcrow's opinion was based upon a detailed finite-element analysis using Abaqus software. Their analysis predicted independent stanchion failure when subjected to a horizontal point load of 15.9 kN. Corrosion was not considered in the failure analysis.

The 1990 physical testing as discussed supports this conclusion.

5. The inquest (2016)

The evidence of the expert to the inquest, Mr John Cutlack, correctly described pens 3 and 4 of the Leppings Lane terrace as a disaster waiting to happen. The historical acceptance, prior to the disaster, of the barrier layout and barrier geometry in pens 3 and 4 undoubtedly demonstrates a failure to understand and apply knowledge that existed at the time. Overcrowding has become the perceived immediate cause (obvious reason of an adverse event). The details that follow indicate that considering the overcrowding as a root cause (an initiating event) would be more appropriate.

6. Crowd density

In both the Taylor inquiry (1989) and the most recent inquest (2016), considerable emphasis was given to the extent that the occupation of the terrace greatly exceeded the capacity calculated in accordance with the Green Guide (Home Office, 1986).

The 1986 edition of the Green Guide allowed for a density of 5.4 persons/m² on a standing viewing terrace that accorded with the guide.

Consider Figure 7, which illustrates six persons standing in single file on level ground. The individuals illustrated in Figure 7 were confined to stand between two fixed horizontal rectangular hollow sections. The horizontal section to the front was instrumented to ascertain the force to each compressed individual given a steady-state condition where the force on each person would be the same.

At the lower packing density, 8.6 persons/m², the resultant compressive loading to each individual was 115 N. At the higher packing density, 10 persons/m², the resultant compressive loading to each individual was 380 N. The peak loading observed as the seventh individual inserted himself into the line was 920 N.

Figure 7. (a) Equivalent to 8.6 persons/m²; (b) equivalent to 10 persons/m²

In pens 3 and 4 on the Hillsborough terrace, the barrier at the front of row 1 (Figure 2(b)) was the perimeter fence. At a density of 10 persons/m² in row 1, the contact arising between persons in row 2 and row 1 had the potential to increase the 'resident' compression of approximately 380 N in row 1.

Figure 8 illustrates the elliptical space occupied by an individual within the 70th–75th percentile adopting anthropometric values provided by Pheasant (1990).

High crowd densities are not always synonymous with unacceptable levels of risk. London Underground (LU) in estimating passenger capacities allows for 8 persons/m² in the standing areas immediately adjacent to doors (Connor, 2011).

Areas near the front of stage barriers at rock/pop concerts can experience densities greater than 10 persons/m². Viot (2015) provides photographic evidence from a concert that illustrates this density. The front of stage area is well known to be high risk and necessitates management measures to be in place to remove distressed individuals as and when required; the audience profile at rock/pop concerts, often relatively young smaller individuals, is also significant.

Norton (1989: p. 5) discusses HSE tests on a level surface.

The tests suggested that a crowd density of 10 persons/m² could be achieved without distress, although the subjects felt they were packed tightly.

Initially the geometry of terrace steps will create a pattern that accords with spectators having sole occupation of a tread as illustrated in the left side of Figure 8. The Green Guide recommends that a terrace step should not be less than 280 mm or more than 380 mm. The preferred dimension is between 355 and 380 mm. A tread depth of 355 mm with a single row of spectators standing on each tread creates a density of 5.4 person/m².

Figure 8. Crowd densities

The average tread depth between barriers 136 and 124A in pen 3 was 388 mm with a maximum of 400 mm. This would create a density of 5 persons/m² with a single row of spectators standing on each tread. Ingress of additional spectators creates unstable equilibrium as some spectators will stand on the nose of a tread.

Figure 8 illustrates to scale the terrace between barrier 136 and 124A with densities of 5 and 8.1 persons/m², respectively. Physical testing previously noted indicates that within the area illustrated there would be a compressive force of 115 N or thereabouts on each individual for the case illustrated in the right side of Figure 8 providing spectators remained upright.

7. Barrier height and spectator lean

A terrace barrier is installed to protect spectators forward of the barrier. Limiting the spacing between barrier rows protects those spectators behind a barrier.

If a barrier height prevents persons on the barrier from leaning, those behind in a closely packed crowd have limited, if any, opportunity to lean. The heights of a number of barriers in pens 3 and 4 were considerably below that recommended by the Green Guide (Home Office, 1986).

Barrier height was briefly addressed during the Taylor inquiry and at length during the most recent inquest (2016). The transcripts of the inquiry (1989) and the inquest (2016) show that the significance of a low barrier height in allowing a 'waterfall' effect was understood, while the magnitude of the forces created by a leaning crowd was not.

During the inquest (2016), the barrister for SWFC, Mr Beer, referred to the work of Evans and Hayden (1971) that established the part of the body that could best take a force when pressed against a barrier. Evans and Hayden (1971) arrived at an optimum barrier height of 1.05 m. Dr Eastwood argued that a barrier height that coincided with the hip bone was more appropriate. The hip bone height for the 95th percentile of the male population is 1 m and 0.92 m for the 50th percentile. This provided the essence of Dr Eastwood's argument, justifying lower barriers, during the inquiry (Home Office, 1989) and the civil case in the Liverpool High Court of Justice (Liverpool High Court, 1989). The ability of an individual to resist a force is not the primary consideration in determining the height of a terrace barrier. The barrier height has to prevent upper body rotation, and a barrier height of less than 1 m does not prevent upper body rotation.

As a surge progresses through a crowd, on level ground or down a terrace, individuals remain standing simply by leaning on the person in front or stepping forward if the density allows. The horizontal force created on a barrier when forward motion is halted varies in accordance with the angles of lean within the crowd behind the barrier. The crowd density and the height of the barrier dictate the angle of lean.

Creasey (1948) experimentally determined a force of 175 N/m for a row of persons leaning on level ground. Subsequent research undertaken for the Home Office (1973) relating to the Wheatley Commission (Home Office, 1972) considered a terrace with a slope of α° and proposed that the force created by a leaning individual was

$$P_{\text{slope}} = P_o + 32.7 \sin \alpha \quad \text{with}$$

1. $P_o = 82.5 \text{ N} (\equiv 155 \text{ N/m per row})$

For a 14° terrace, the lean force increases to 170 N/m per row. Angles of lean were not specified in either case.

In relation to the Hillsborough disaster, lean forces were addressed by Smith and Games (1989), who developed an original and informative model for a leaning crowd. Using their model on level ground, a force of 82.5 N would result for an ‘average’ person leaning at 8° . When considering a crowded terrace, the Smith and Games model also incorporated the influence of the stepped nature.

A leaning crowd creates a force on the individual immediately behind a barrier. If the barrier height is sufficiently low to allow that individual to lean, the obvious consequence is that those behind increase their lean. The resultant increase in force on the individual immediately behind a barrier considerably exceeds the small advantage to that individual arising from a lower barrier height.

The significance of lean that would arise due to low barriers in pens 3 and 4 was only partially recognised; this factor is separate from the waterfall effect described by James (Nicholson, 1989), Dickie and Wanless (1992) and clearly explained by Cutlack during the inquest (2016).

Wanless (1992) describes physical testing studies concerning surge forces on barriers. Figure 9 illustrates the characteristic of the loading to a terrace barrier following the unstable forward movement of the spectator body behind the barrier. The tread depth was 280 mm, which allowed for a density of 6.7 persons/m^2 .

The surge element reflects the kinetic energy of the spectator body toppling downwards. A loosely packed crowd that topples downwards on a terrace can generate more kinetic energy than a tightly packed crowd. When stability is restored the ability to lean, where a barrier height complies, of those to the rear of the spectators on the barrier is reduced as the crowd density increases. The attainable angle of lean of those within the crowd is dependent on the spectator density in addition to the barrier height.

On a mock 15° terrace with a tread depth of 355 mm, the recorded surge and lean forces on a 1.05 m high barrier were reported by Wanless (1992). The surge was initiated by the rearmost persons leaning forwards, and for different packing configurations, the forces were as those shown in Table 5.

Figure 9. Surge characteristic

Dickie and Wanless (1992) modified the Smith and Games model in order to take into account a high crowd density on a terrace where spectators stepping down could be incorporated. Stepping down increases the density and decreases both the surge and the lean forces.

If the barrier height accords with the Green Guide recommendations, 1.02–1.12 m, the individual illustrated in Figure 10(a) cannot rotate. A low barrier, <1 m for 95th percentile, does not provide this benefit. The individual immediately behind the lower barrier rotates, and the degree of lean determines the force P_2 created by spectators to their rear, $P_2 > P_1$. If the individual in Figure 10(a) were to be in contact with a spectator forward of the barrier, then P_2 will in part pass across the barrier.

The crowd configuration illustrated in the left side of Figure 8 can be described as relatively stable, and the loss of an individual’s position due to crowd dynamics forcing forward movement is recoverable. A spectator forced to step forward, leaning or toppling onto the person in front, would subsequently be able to recover their original position.

If forward movement is triggered within the higher density illustrated in the right side of Figure 8 and barrier 124A were not to be of sufficient height, some forward movement could occur as illustrated in Figure 11.

8. Asphyxia

There are no definitive data for the asphyxia threshold. The design force for a barrier in pens 3 and 4 on the Hillsborough terrace was 5 kN/m. This is the design load previously referred to which together with a proof load = $1.2 \times$ design load provides the

Table 5. Surge and lean forces for different packing configurations

Persons/tread	Surge force: kN/m	Lean force: kN/m
1, 1, 1, 1, 1, 1	6	2.5
1, 2, 1, 2, 1	3.5	1.9

Figure 10. Significance of barrier height: (a) non compliant barrier allowing lean and (b) compliant barrier preventing lean

barrier test loads specified in the third edition of the Green Guide (Home Office, 1990). The design load value was derived from a Home Office (1973) report where evidence was discussed concerning a fatality resulting from a force of 300 lbs (1350 N) applied over an interval of 4–6 min. The design force was related also to fatalities that were reported at the 1946 Bolton Wanderers disaster (Hughes, 1946) where layers of three to four bodies were sufficient to cause death by traumatic asphyxia. This resulted in a barrier design force of 340 lb/ft (4.96 kN/m) being adopted following the Wheatley inquiry (Home Office, 1972).

Oberhagemann (2012) considers a lower value of 800–900 N sustained over a period of time would suffice to be potentially fatal. Peak loadings of 4.2 kN/m on a front of stage barrier at a heavy rock concert were reported by Hopkins *et al.* (1993). The historical evidence is that a terrace barrier design force of 5 kN/m is appropriate.

If the height of barriers 136 and 124a had accorded with the recommendations of the Green Guide edition applicable at the time (Home Office, 1986), then the forces on them would have

Figure 11. Result of surge between barriers where initial density was 8.1 persons/m²

been relatively similar. As previously discussed, the level of force applied to an individual standing upright behind a barrier depends on the extent of lean of those behind. Where the barrier height is compliant, the greater the crowd density behind the barrier, the lower the angle of lean. Where the density is less than 8 persons/m², an increase in spectator density does not necessarily result in an increase in the level of force if the barrier height is compliant (Dickie and Wanless, 1992).

Barrier 149 (see Figure 2) was of the type illustrated in Figure 10(b), having a height above the body's height of rotation. In the event of a forward surge within row 4, the crowd in row 4 (density 7.5 persons/m²) would have been contained with no force being transferred over the barrier; the forward surge would have been halted.

The effective height of barrier 136 was 0.83–0.86 m. The preferred Green Guide height was 1.1 m.

The effective height of barrier 136a was 0.85–0.87 m. The preferred Green Guide height was 1.1 m.

Referring to Figure 2 in the event of forward surge in row 3, an individual immediately to the rear of barrier 136 would have been forced to rotate over the barrier and lean into a person in row 2. The waterfall effect would have triggered the surge to continue down the terrace.

Figure 7 indicates that the density of the spectator mass in row 2, 8.1/m², would have allowed for compression of the spectator body as a whole. As the spectator body in row 2 was compressed, the extent of the forward movement of individuals immediately forward of barrier 136 would have resulted in barriers 136 and 136a either

partially or fully containing the lean force arising within row 3. The extent of physical contact between spectators immediately to the rear of a barrier and spectators immediately forward of the barrier dictates the fraction of the force that spills over the barrier.

The terrace in Figure 11 relates to row 2 as denoted in Figure 2, where there were eight terrace steps and a part step. A surge down the terrace where all individuals lean and some step down a tread could result in the spectators being arranged as illustrated in Figure 11. The resultant force on the barrier using the analysis of Dickie and Wanless (1992) predicts that a compliant barrier would be subjected to a lean force of 2.33 kN/m. A non-compliant barrier height that promotes an additional 5° lean within the spectator body in row 2 would increase the force to 3.5 kN/m, part of which would ‘spill’ into row 1.

The Taylor interim report (Home Office, 1989: p. 13) stated

Surges on terraces are common. Usually, they go forwards and then recede. Here with the weight of numbers, there was no receding. The pressure stayed and for those crushed breathless by it, standing or prone, life was ebbing away. Many fans were bent painfully over barriers under great pressure.

Coupled with the resident compressive force present in a crowd with a density of 10 persons/m², the additional force overspill from row 2 arising from spectator lean results in the traumatic asphyxia threshold being exceeded in row 1. It is important to recognise that the lean force is the horizontal force when motion within the ‘collapsed’ crowd ceases. The term ‘collapsed’ describes the situation where all individuals in the crowd have to lean into the person in front to maintain their equilibrium. The surge factor, while temporary, can be considered to increase lean forces by a factor of 2.

Gill and Landi (2004: p. 358) discuss numerous crowd incidents that resulted in fatalities. Of relevance is that concerning a community basketball game in New York City.

At one point, the inner admittance doors were locked, and a surge of several hundred people tried to get down the single stairwell that entered the gymnasium. The 4 steel doors at the bottom of the stairs were closed, and the people in the stairwell were trapped and compressed.

The cause of death of all nine decedents was asphyxia by chest compression.

The consequence of the pitch perimeter fence at Hillsborough would have been identical to that of the locked doors described by Gill and Landi (2004).

The lateral gap between barriers 136 and 136a was 2.235 m. This width considerably exceeded Green Guide recommendations and would have created forces on barrier 124A above the design requirements.

Where there are gaps in the line of crush barriers these should be at least 1.1 m and not more than 1.4 m in width (Home Office 1986: p. 36).

Subjected to a uniformly distributed static load, the behaviour of barrier 124a under increasing load would have been as follows. Using the plastic moments of the horizontal rail provided by Smith and Games (1989), a plastic hinge would form in the rail at position 2 (see Figure 12) under a loading of 2.85 kN/m. A second plastic hinge would occur in the rail at position 3 under a loading of 4.5 kN/m. The formation of these hinges means that these bays can be considered to act independently.

Adopting the observed densities, the gap between barriers 136 and 136a created 28 rows of spectators, four abreast, between barriers 149 and 124a and the load applied to barrier 124a would not be uniform.

This writer analysed barrier 124a and incorporated the development of plastic hinges in the horizontal rail to obtain the resultant post reactions. For the hypothetical loading shown in Figure 12, the required post reaction at position 3 is 16.05 kN, which, given the experimental evidence, would most likely result in the collapse of the stanchion. The loading characteristic illustrated in Figure 12 is simply considered as one that could create the reaction likely to initiate the collapse of support 3 or 4.

Various analyses of the failure load of barrier 124a have been undertaken. Halcrow’s (1990) detailed finite-element analysis, previously referred to, predicted that the barrier would have collapsed at or about 6 kN/m. The proof tests following the disaster indicated that the ability of barriers to resist a load of 6 kN/m was questionable.

The actual pattern of loading that resulted in the failure of barrier 124a is not determinable, and there would have been both horizontal and vertical components. Initially a significant proportion of the lean forces emanating from row 2 would have been resisted by the spectator body in row 1 as a consequence of the crowd density forward of the barrier and the nature of the perimeter fence. Any lessening in this resistance would have increased the forces applied to barrier 124a as the lean of those to the rear of barrier 124a increased.

Figure 13 illustrates barrier 128 in pen 4 (see Figure 2) following the disaster. Barrier 128 was in line with the collapsed barrier

Figure 12. Hypothetical loading distribution

Figure 13. Barrier 128, pen 4, post-disaster

124a in pen 3. The plastic deformation of the horizontal rail in barrier 128, evident in Figure 13, is present in the same bay that collapsed in barrier 124a. The loading history that resulted in the plastic deformation would probably have been created by successive crowd surges. The gap between barriers 137 and 138 was 1.7 m as opposed to a 2.2 m gap between barriers 136 and 136A. Barrier 137 protected the deformed bay in barrier 128 to a greater extent than the protection afforded to barrier 124a by barrier 136.

Lord Justice Taylor (Home Office, 1989) also considered the single-bay barrier 144, of 1.08–1.1 m height, could have been beneficial.

As previously stated, Norton (1989: p. 8) from an extensive study of photographic evidence incorporating head counts concluded that

at 15:00 hours the packing densities in Pens 3 and 4 were nominally the same.

Less than 20% of the fatalities occurred in pen 4 (Dickie and Wanless, 1992).

Barrier layout in pen 4 can only be described as piecemeal and shows little understanding concerning the control of crowd pressures on a terrace; nevertheless, while still far removed from compliance, the barrier arrangement in pen 4 considerably increased the level of spectator safety compared with that provided in pen 3. As previously commented on, the arrangement in pen 3 provided 44% of Green Guide recommendations with regard to barrier height and layout compared with 59% in pen 4.

The scale of the reduction in the number of fatalities in pen 4 is considered attributable to the increase in barrier provision.

9. Conclusions

The occupancy of the Leppings Lane terrace at the time of the Hillsborough disaster considerably exceeded the guidance provided in the *Guide to Safety at Sports Grounds*, second edition, applicable at the time. The following are the conclusions.

- Deviations from the Green Guide recommendations concerning barrier geometry and layout on the Leppings Lane terrace, necessary to provide adequate spectator safety, demonstrate poor professional judgement.
- The third edition of the *Guide to Safety at Sports Grounds* (Home Office, 1990) that followed the Hillsborough disaster recognised the need to change the barrier testing procedure. The revision ensured that bedding-in deformations could be distinguished separately from deformations attributable to plasticity.
- The ramification of increased spectator lean that the non-compliant barriers promoted was only partially understood by the inquiry (1989) and the inquest (2016).
- The overcrowding of the terrace, while a significant component with regard to the Hillsborough disaster, should be considered as a root cause (an initiating event) rather than the immediate cause (obvious reason of an adverse event).

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