SOUTH-EASTERN AND CHATHAM RAILWAY.

Board of Trade, Railway Department,
8, Richmond Terrace, Whitehall, London, S.W.,
25th March, 1906.

SIR,

I HAVE the honour to report, for the information of the Board of Trade, in accordance with the Order of the 6th December, 1905, the result of my inquiry into the circumstances attending the fall of part of the roof of Charing Cross Station, on the South-Eastern and Chatham Railway. The fall occurred about 3.45 p.m. on the 5th December last.

A length of about 77 feet of the roof fell, comprising the two end bays at the south of the station. A gang of men were employed at the time in repairing, glazing, and painting the section of the roof which fell.

Shortly after 3.30 p.m., a loud noise was heard in the roof, and it was noticed that one of the tie rods of a main principal had broken, and was hanging downwards. No apprehension was caused in the minds of the observers of anything more serious than the possible fall of this broken rod. About twelve minutes afterwards, two complete bays of the roof, together with the large wind screen at the river end of the station, collapsed. That part of the western station wall above platform level, which carried the bays in question, was thrust outward by the falling roof, overturned, and crashed bodily through the adjoining wall and roof of the Avenue Theatre. The theatre was in course of reconstruction at the time, and a large number of men were engaged on the work.

The roof girders and débris fell across four passenger trains, standing at Nos. 3, 4, 5, and 6 platforms respectively, and completely blocked all lines of way. Fortunately, although some of these trains were being loaded at the time, all the passengers and railway men escaped without injury.

But two of the Company's workmen employed on the roof were killed, and an employé of Messrs. W. H. Smith & Son was mortally injured, and died shortly afterwards in hospital. In the Avenue Theatre also, there was the sad loss of three lives—two workmen killed instantaneously, and a third who died of his injuries.

Eight other workmen were seriously injured and detained in hospital, and nineteen more suffered in a less degree from cuts and bruises.

Description.

Charing Cross Station roof was constructed about the year 1863 from designs by the late Sir John Hawkshaw. The station is built on a brick arched viaduct, and lies generally in a north-west and south-east direction. The level of the rails above the ground varies from 13 feet at the north-east end to 27 feet at the bridge abutment at the south-east end.

The roof measured 510 feet in length, with a clear span of 164 feet. It rests on brick walls, which are carried by the viaduct, and have a height of $41\frac{1}{2}$ feet above rail level.

The roof is designed as a contained arch, and the principals are of the crescent bowstring type, with vertical members and braced panels.

There were altogether 14 principals, and a wind screen girder at the river end. The central interval between the end girder and the first principal was $41\frac{1}{2}$ feet; between the first and second principals, 37 feet; between the second and third, 36 feet; and between the remaining principals, 35 feet.

The end screen and each principal rest upon pilasters built of stock bricks in alternate layers of mortar and cement; these layers average about 4 feet in thickness. The pilasters measure 9 feet in length, and from 3 feet $8\frac{1}{2}$ inches to 2 feet $10\frac{1}{4}$ inches in thickness; between the pilasters the side walls are built up of brickwork with relieving arches.

The roof arch has a rise of 45 feet above the side walls, and the maximum depth of truss in each principal is 20 feet.

Each principal has a curved plate girder compression rib consisting of $\frac{1}{2}$-inch web plate, 18 inches deep, with four angle irons, $6 \times 3 \times \frac{3}{4}-\frac{9}{16}$ inches. Eight verticals divide the truss into nine panels; these verticals are made up of two ⊥-irons, $6 \times 3 \times \frac{1}{2}$ inches. The seven central panels are braced diagonally with two flat bars, $4 \times \frac{3}{4}$ inches. The panels are completed at the bottom by straight lengths of round tie rod. These tie rods vary in size. In the case of the principal which fell, commencing from the side wall to the centre, the diameters of the tie rod, panel by panel, were: 5, $4\frac{3}{4}$, $4\frac{1}{2}$, $4\frac{3}{8}$ and $4\frac{1}{4}$ inches. The two ends of adjoining rods are screwed into muff couplings, to which are attached the vertical members and the diagonal braces.

On the main ribs rest longitudinal lines of purlins, spaced at intervals of from 8 to 11 feet apart. These are built up of four angle irons, $3\frac{1}{2} \times 3 \times \frac{1}{2}$ inches, with flat lattice bars, $2 \times \frac{3}{8}$ inches. The purlins are stiffened laterally between each pair of roof principals by two lattice girder common rafters. These run from the walls up to the purlin girders which support the lantern roof.

Sash bars of T-section, $3 \times 3 \times \frac{7}{16}$ inches, spaced at central intervals of 1 foot $6\frac{1}{2}$ inches, rest on the purlins, and support the zinc and glass covering of the roof.

Ventilation is provided for by a continuous lantern on the crown of the roof, which has a width of 18 feet, with a height to the ridge plate of $9\frac{1}{2}$ feet, with louvred sides.

The roof, with the exception of the actual covering, is constructed entirely of malleable iron. There are no wind ties to resist wind pressure, other than the additional diagonal bracing in the panels of the principals.

The feet of the main trusses are fixed on the eastern wall. The western footings, which rest on suspension link saddles, were designed to be free to move under the force of expansion and contraction. As a matter of fact, it was found that this arrangement has not worked as was intended, and the walls must therefore have yielded to the force of expansion and contraction.

The wind screen consisted of a box girder with a built up plate flange as the bottom member, without tie rodding. The ends of this girder rested on the two southern pilasters at the same level with the main trusses.

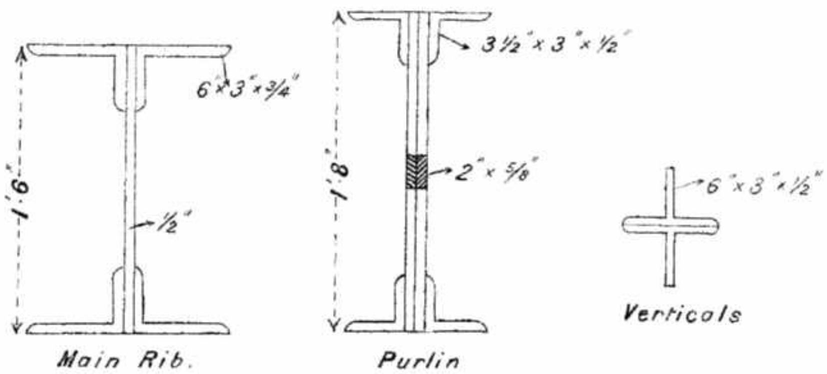
Sketches of the principal which fell, and of the fractured tie bar, will be found on Plates I and II, and a table of stresses in the Appendix to the Report.

Evidence taken on 9th December.

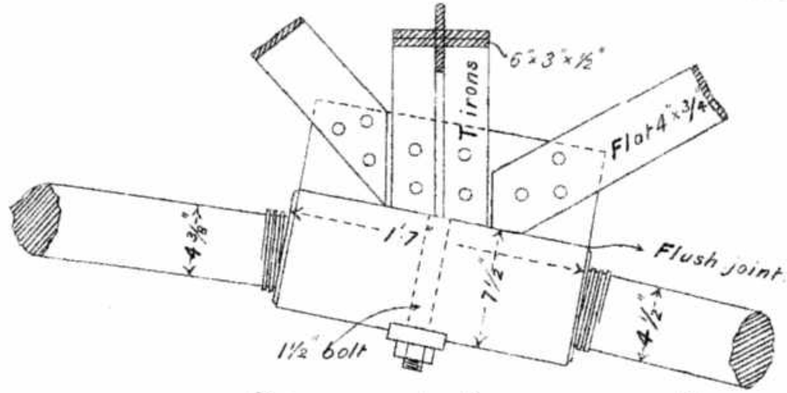
George Coulson Stirling, states: I am in the engineering department of the Railway Company, as foreman of the bridge section. I have about 13 years' service. I have been foreman for five or six years, and was charge-man previously. I have a gang of about 62 men. At the time of the accident 10 of these were employed on the roof at Charing Cross Station. In addition to these men, who were employed on overhauling and repairing work, such as cutting out iron and replacing it, and rivetting, I have charge of a gang of painters, glaziers and plumbers. There were 15 of these men altogether working—11 painters and four plumbers. The repair work at Charing Cross Station began in July last, and I have since then been employed on it continuously. We began work at the south end of the station roof—that is the river side. I was in charge of similar work repairing Cannon Street Station roof. I was employed on that roof about 18 months continuously. That was completed in March last. My instructions as regards the work at Charing Cross Station were as follows:—To cut out and renew all glass, to scrape all iron work, and to give three coats of paint. As regards the renewing of iron work, my instructions were to replace the sash bars where necessary, and to renew the lattice stiffeners situated between the purlins, where the iron work had been rusted thin. We had put in 28 lengths of these lattice girders, which were the total number required for the repair work of the two lines of stiffeners in one bay. In the bay of the roof nearest the river there was no glass in the roof, the roof being covered with boarding and zinc sheets. We had repaired the wood where necessary, and renewed practically all the zinc sheeting. We had actually almost completed the whole of the work in connection with the south end bay. The stages were about 35 feet long by $12\frac{1}{2}$ feet wide. There were altogether 18 of these stages; 16 of them were 35 feet by $12\frac{1}{2}$ feet and two in the centre were 35 feet by 20 feet. Each of these stages was made up of two portions, divided where necessary by the ironwork of the principal. They were suspended to the main purlins by 12 hanging irons $1\frac{1}{8}$ inch in diameter. At the time of the accident on the 5th December 20 of my men were working. Of these 16 were distributed over the stages, and four were on the roof outside renewing the zinc sheets. To provide means of communication for the men, there was a continuous ladder fixed outside the roof close to the first principal. The men got through the roof on to the stages from this ladder. There was a man down below, on the station platform level, to warn people on the platforms in case anything fell from the stages, or the roof. I did not receive any special instructions except as regards strutting between the purlins before removing any of the stiffeners which had to be renewed. Also to keep the additional weights on the roof as low as possible. During the five months or so that I was at work I had heard no sounds in the roof to lead me to suppose there was any weakness in any portion of it. I personally examined the condition of the iron work in the roof, and found the iron work in the main rib in very good condition. The paint had perished, and could be peeled off with the fingers—at least, much of it could be peeled off easily. There was very little rusting going on in this part of the roof except at the outer points of the angle irons of the purlins. I looked also at what I could see of the struts and the lattice ties. They also were in very good condition. Such rusting as had taken place was at the outer edges, and there were some pock marks on the flat surfaces of the ironwork. As regards the tie-rods, I had only been able to examine those of the two side panels nearest the wall in each case. The eastern

Sketches of Station Roof.
Charing Cross.

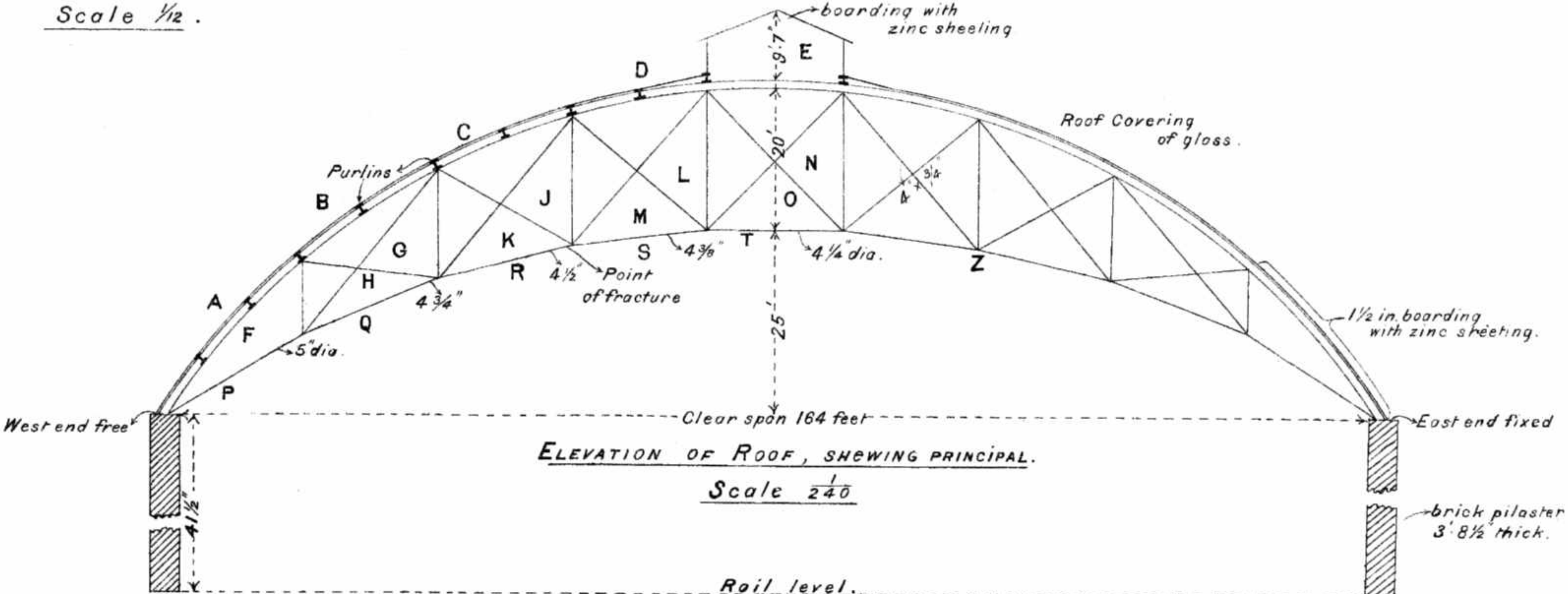
Sections of Ironwork



Scale 1/12.



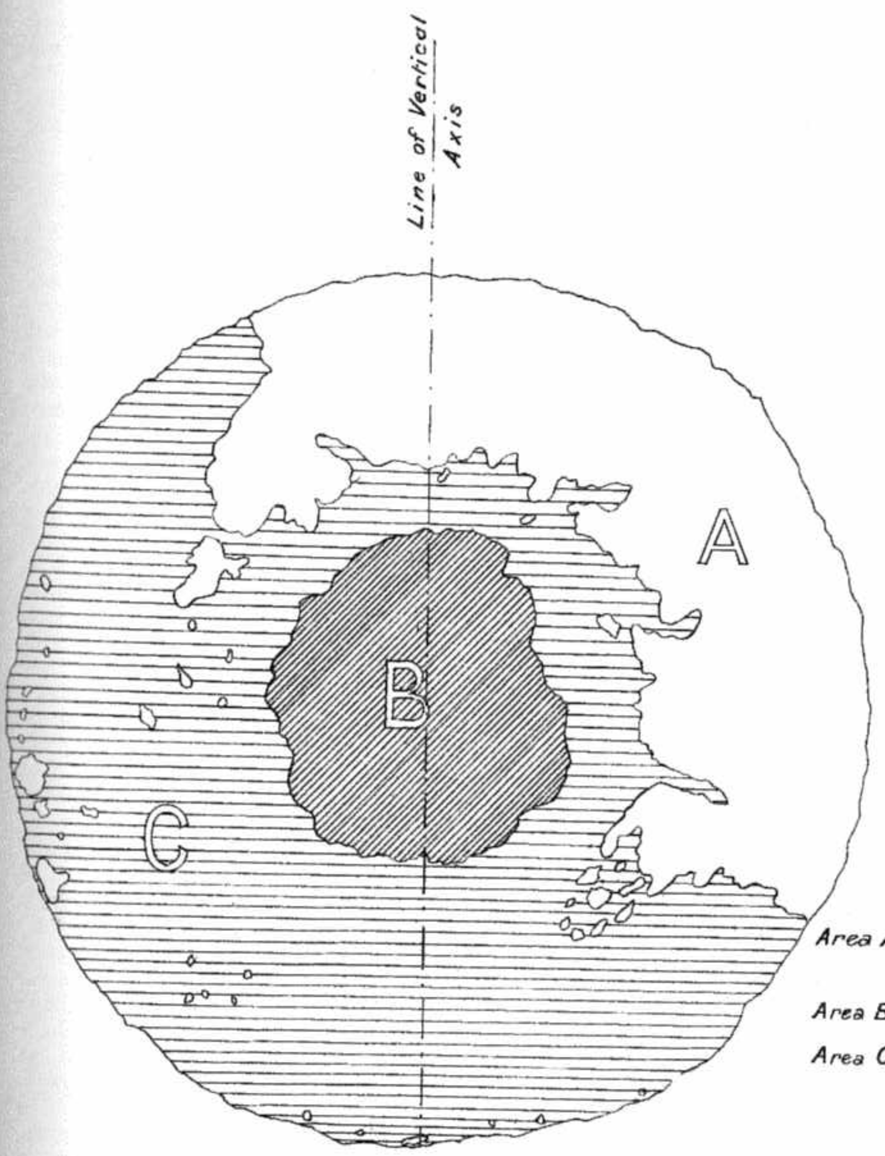
Elevation of Coupling at Z.



Elevation of Roof, shewing principal.

Scale 1/240

Weller & Graham Ltd Litho London



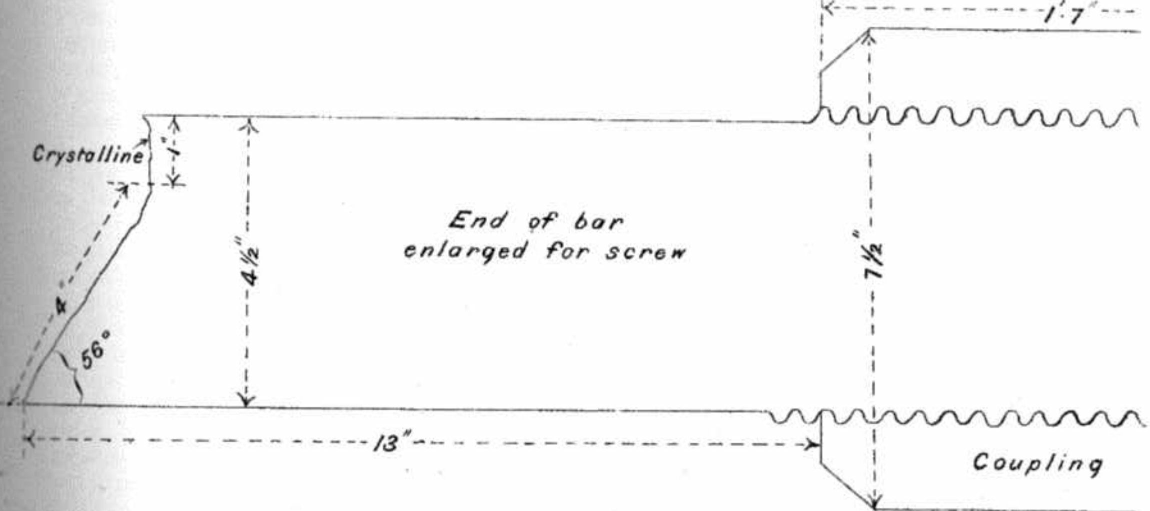
Area A – bright crystalline appearance of freshly fractured iron.

Area B – pocket or original flaw in weld

Area C – discoloured surface, over which flaw extended.

SKETCH OF FRACTURED SURFACE (WEST END) OF TIE ROD.

Scale full.



LONGITUDINAL SECTION OF FRACTURED TIE ROD.

Scale one third.

tie-rod of these had been stripped of paint, and was in good condition. The other had not been stripped of paint. None of the nuts or screws holding the collar joints of the tie-rods had been in any way loosened or removed.

Mr. William E. Maskell, states: I am employed by the Admiralty in the Director of Works Department. My room is on the third floor at the back of Craven House, from which there is a view of the south-west end of Charing Cross Station wall, which is about 40 yards distant, through a gap between the Avenue Theatre and the houses in Craven Street. On the 5th December, I and two other gentlemen in my room heard a crash which appeared to come from the street below. This, as far as I can judge, was about 3.35 p.m. The first thing after the noise that drew our attention was a number of men climbing up a ladder on to a gangway at the top of the roof. We then noticed that the crown of the roof was sagging, as if a depression was forming near the crown, and this seemed to take place in the portion which had just been recovered with zinc sheets. I looked at my watch and found the time to be 3.45 after I had been watching the roof for what appeared to be about 10 minutes. The actual collapse did not take place for some few minutes afterwards, possibly 3.50 was the time, so that I estimate about a quarter of an hour elapsed from the time we heard the first crash to the actual fall of the wall and roof. We could see from the window about half the height of the station wall between the second and third pilaster, counting from the south, and I saw a crack commencing close to the bearing of the truss which is still standing. I saw the crack in the wall commence to widen, and then I saw bits of brick and plaster falling out. I could see the whole of the roof to the south end of the station, but of the wall only as far south as halfway between the second and third pilasters. The last portion of the roof that seemed to fall in was the screen at the end. It appeared to me, seeing the interval that elapsed, that there was time for all the men working to have escaped, but I noticed that some of them were, as I thought, called back for some reason. I noticed that the men on the roof were using portable forges, and it occurred to me that they might have removed some integral part of the roof, and thereby caused the fall.

George Coulson Stirling (recalled), states: The remainder of the tie-rods were to have been inspected subsequently by means of cradles lowered from the stages. I was in my office or cabin over the tank, on the east side of the station, about 3.30 p.m. on the 5th December, when I heard a noise as if something had struck my cabin. It was a strange noise, and I rushed out to see what was the matter. I saw the men coming off the stages and down the ladders, and I asked them what was the matter. They said that something was wrong with the roof, as the staging was giving way a little. I rushed right up the ladder over the crown of the roof, and dropped down into the stage in the sixth panel of the principal counting from the east. This was the easiest to get at. I saw that the lattice diagonal brace nearest the centre of the roof was broken. The two broken ends were about 1½ inches apart then. Immediately I called down to the watchman on the platform to clear the people away from underneath. He heard me and answered me twice. I then got a rope, and fastened it to the broken brace to prevent its falling in case it broke off. Some of my men had followed me back up the ladder, and I told them to clear away two or three piles of zinc sheets that were lying close to the screen. All of these were, I believe, clear of the staging—but I thought it advisable to lighten the roof. There were about 25 to 30 sheets of zinc in each pile. The men began to move them down, and I helped them. They also began to remove sheets of glass out of a crate which was on the crown of the roof, about 15 feet from the principal. I had just reached the gutter at the tank side of the roof, when I saw the iron channel cracking, and I shouted to the men to come down. There might have been five or six men on the roof at the time. I do not remember anything more until after the fall of the roof, when I found myself just above the tank outside the wall. When I was on the staging I could not see the main tie-bar underneath without kneeling down, and I thought at first that the danger was merely of this lattice brace breaking off and falling below. I did not notice any sagging of the roof. I should say that the whole time that elapsed between hearing the first noise, and the fall of the roof would be ten minutes. Underneath each of the stages were hung canvas bags for the safety of the men at work. The platforms down below were protected by light structures of woodwork covered with curved corrugated sheeting. My instructions, as regards the principals, were to scrape, clean, and repaint all the members, but not to renew, cut out, take away, or replace any of the iron work without first reporting the necessity for doing so.

James Henry Edge, hammerman in the engineer's department, states: I have been employed as hammerman for six years. About 3.30 on the 5th December, I climbed up the ladder outside the roof on to the crown. I was returning after completing another job. I saw Mr. Stirling on the crown of the roof coming towards the ladder with a zinc sheet. I went on up the ladder to the crown, and then heard a loud report, followed by a rumbling noise. Then I shouted out that the roof was falling, and ran away along the gangway on the crown of the roof towards the hotel. I had been employed on the Charing Cross Station roof for some weeks off and on, and had been also employed during the past 18 months on similar repair work at Cannon Street Station. My work was chiefly in connection with helping to fix up the stages, and cutting out rivets and bolts when required. I noticed a crack in the iron channeling at the top of the wall, before beginning to go up the ladder, but at the time I did not think anything more of it. All the time that I was employed on the roof at Charing Cross Station previous to the day of the accident, I did not notice any noise which would denote anything dangerous in the state of the roof. I do not remember seeing anybody on the roof at the time I shouted out that it was falling, except one man who ran along the gangway with me.

Nathaniel Hobbs, labourer in the employ of the engineer's department, states: I was working on the stage that was hung in the fourth panel from the west. I was scraping the iron work. I heard a loud "bang." I did not know what the noise was, but I noticed that the scaffolding seemed to drop a little. I thought that something had gone wrong with the stage so I climbed on to the roof, and got down the ladder. I met Mr. Stirling as he came from his office. He asked, "What is the matter?" I did not stop. Someone else answered him. I thought something had gone wrong with the scaffolding, and I was afraid to go back. I had been working for several weeks on the roof, but I had not during that time heard any sort of noise that was uncommon or called for attention.

David Bunn, signalman at Charing Cross box, states: At 3.44 p.m. on the 5th December, I was looking towards the station, and saw the west side of the roof falling. The wind screen afterwards fell towards the north. The last train to leave No. 2 platform was the 3.35 p.m. for Hastings. This train left at the proper time. An up-train arrived at No. 6 platform at 3.39. There were no other movements in the station in or out between 3.35 and 3.44, when the roof fell in. Before 3.44 I heard no noise to draw my attention to anything in the station or roof. At 3.45 I blocked back to Belvedere. I had the 2.5 p.m. up-boat train from Folkestone offered to me at 3.45. I did not accept it.

John Thomas Woodland, chief platform inspector at Charing Cross Station, states: I had no warning of anything being wrong before the accident happened, and it was on returning from No. 2 platform to the square, that I heard the noise of the roof falling. At first I thought that it was an engine boiler that had burst. I immediately sent to the hospital for assistance.

John Setterfield, guards' inspector at Charing Cross Station, states: About 3.30 p.m. on the 5th December, I was in my office above the bookstall when I heard a slight report. It was different from other station noises, and I called the attention of my mate who was in the office to it. He thought that it was a train running into the buffers, but I did not think so, as there was nothing moving in the station. Nothing more happened then, and I went on with my work. About 3.45 I heard a loud noise as I was sitting looking up the station. I looked up and saw the wood staging, on which the men were working, beginning to fall. The roof immediately followed, the last thing to fall was the screen at the end. There was no warning to anybody on the platforms, to my knowledge.

Harry Stone, platform inspector at Charing Cross Station, states: I was on No. 6 platform about 3.30 p.m. on the 5th December. I heard no shouting from the roof. About 3.34 I heard a report like a gun-shot up in the roof. I looked up and saw one of the tie-rods broken and hanging down. It appeared to be over No. 2 platform. It was only the tie-rod of one panel that was broken. I then looked up to the roof, and noticed that it was slightly bending inwards. This was immediately after the 3.34 p.m. train had arrived. I then went over to Nos. 1 and 2 platforms across the rails. I told Hatch what I had seen. I could see that the tie-rod was broken standing on Nos. 1 and 2 platforms, but the bend in the roof was not visible. I went back to No. 6 platform as I had the 3.39 train to book out, and as I passed on my way I cautioned other men. When I got to No. 6 platform, I could see the roof was more bent than before. The 3.39 train went out, and the 3.43 came in at the same platform, No. 6. Then a man who had come down the ladder from the roof came from between the carriages standing on No. 6 line, and he said, "Look out, governor, the roof is all coming down," so I turned and ran inwards with others who were on the platform. There were no noises going on in the roof, or glass falling, after the first report occurred until the whole roof fell. There was a man at the head of No. 2 platform who was on the look-out for danger from falling articles. He was one of the people I spoke to, to draw attention to the bending of the roof. I went across to No. 2 platform because I thought that there was some danger of the broken tie-rod falling. I did not think there was much danger at No. 6 until the man came down the ladder, and said that the roof was falling.

William Edward Goodchild, yard foreman at Charing Cross Station, states: I was standing at the door of our lobby, which is under the Charing Cross signal-box, about 3.30 p.m. on the 5th December. About this time I heard a loud report. At first I thought that an engine or train had run into the buffer stops. But I at once remembered that there was nothing moving in the station, and, therefore, it could not have been anything striking the buffers. I recognised it as an unusual noise. The next thing I saw was some platelayers running towards the station. I got on to No. 1 platform under the covered way, and saw a stay broken, I understand it is called a tie-rod. To the best of my recollection it appeared to be broken in the 4th panel from the west wall, close to the eastern coupling, and to be hanging from the second coupling joint. It appeared to have broken away from the third coupling joint. I did not think it was anything serious, and I went outside again. I saw all the men come down the ladder from the top. Several went back again. I saw a rope being dropped through the roof, and I thought it was meant to catch hold of the tie-rod which was hanging loose, and to hold it up. I then went back to the box. About 3.45 my attention was again attracted by a second report, much louder than the first, and I looked up and saw the roof fall. I saw there were two men on the top as it fell. I noticed there was confusion, not only among the workmen on the roof, but also among the people on the platform, when the first report occurred.

Harry Cock, out-door assistant to the locomotive superintendent, states: I arrived at Charing Cross by the train due at 3.34, which was about a minute late. I walked off No. 6 platform into the yard where the locomotive foreman usually stands. He was not there, so I walked towards No. 1 platform. I was met by inspector Stone, who informed me that a tie-rod in the roof had broken. I said to him, "I will go and look at it." On walking further up No. 1 platform I met locomotive foreman Neve. He also told me a tie rod had just broken, and asked me if I could see it. I could not see it from where I was standing, and I walked further along the platform and stood almost immediately under it. I could not see it from the head of the platform on account of the darkness under the roof. It was not until I got nearly under it that I could see that the tie-rod was broken, and hanging down. To the best of my memory it was broken between the second and third vertical stays. It was hanging down from the second stiffener from the wall. I then heard a rumbling noise overhead. I turned to foreman Neve and said "Look out, I believe there is some more coming," and we only just had time to escape. We ran outwards to the south, and I was struck by something in the back. I noticed no fall of glass, nor of any articles whatever previously. I am still of opinion that the break occurred between the second and third stiffeners. Of course, I cannot be absolutely certain, but from where I stood on the platform that was my impression.

Benjamin Barber, police constable in the railway service, states: On December 5th I was checking tickets at Nos. 3 and 4 platforms, about 3.30 p.m. I heard no unusual noise in the station. Police constable Fitt came to me from No. 2 barrier, and pointing to the stay or rod, he said, "Did you notice that stay was broken there?" I saw it when he pointed it out. He said he would go and see what was the matter. He then started to go up No. 2 platform. About ten minutes later, as far as I can remember, I heard a loud crash, and I also saw glass falling. Then the whole roof appeared to collapse and come down. As near as I can tell the stay was hanging over No. 2 platform.

William Fitt, police constable in the railway service, states: I was standing on No. 2 platform at the barrier about 3.30 p.m. on December 5th, when I heard a sharp report like a gun. It seemed to come from the south end of the station. I looked round towards that end of the station, and noticed that one of the stays was hanging down as if it had been broken. The train went out at 3.35. I then went to the middle barrier. I spoke to Barber, the foreman, and asked him if he had heard the noise. He said "No." I pointed to the roof and showed him the stay hanging down. I might have stayed with him two minutes, and I then went to No. 2 platform to see what was the matter. I saw the stay hanging down from the roof. As I stood on No. 2 platform it appeared to me that it was the tie-rod in the third bay from the wall that had broken, and was hanging down from the right hand coupling. There was no noise at all, nor anything falling except dust. Some dust went into my eye, but beyond dust I noticed nothing falling. I stopped there some little time, as I thought the rod might break off and fall, and so I stopped people from coming that way. I waited on until I heard a terrific noise. Someone shouted "Run," and I ran down the platform towards the hotel. I was looking at the clock when I heard the first report and I should say it was 3.32 or 3.33. Just before I started to run I noticed that it was about 3.45. I looked at the clock on the second occasion because I was due back to assist Barber at No. 2 barrier. The actual fall of the roof did not take more than a few seconds of time from the moment that I heard the second report.

William Lowes, platform inspector, states: I was on No. 2 platform about 3.30 p.m., on December 5th, starting the 3.35 Hastings down train. About 3.32 or 3.33 I was under the temporary corrugated roof at No. 2 platform when I heard something falling on the corrugated sheet iron. It was an unusual noise. I then started the 3.35 train out. My attention was drawn to some part of the roof that was hanging down by friends of passengers travelling by the 3.35 train. As far as I can judge, the tie-rod was broken between the second and third stiffeners. It had broken away from the second coupling joint, and was hanging from the first coupling joint. Mr. Porter, gas foreman, came up and said that he thought it dangerous for any train to come in to that platform. We were then expecting the Folkestone boat train to arrive. I walked back with him, and he advised me to get the continental train into No. 2 platform instead of No. 1 for fear of accidents. I started to go to the telephone office at the north end of the station, but before I had got half way back I heard a crash, and the roof came down. There were no passengers or other people standing on Nos. 1 and 2 platforms. I should say that the time of the second crash was about 3.45. I can remember the time, as I looked at the clock, before starting towards the telephone office, to see how long there was before the boat train, which was due at 3.50. It was then 3.45.

James Porter, foreman of the gas and plumbing department, states: About 3.30 p.m. on the 5th inst. I had climbed up the ladder leading to the top of the east wall, where some of my men were working, when I heard a report like a gunshot and I felt the gutter shift. I went part of the way up the ladder to the roof to see what the noise was, and then I met the painter coming off the roof. I asked him what was the matter. He told me that something had gone—a girder broken, or something of that sort. I went back down to the station to see if anything was hanging which might be dangerous. I went down to the bottom, and passed under the station by the cab road and came up the cab entrance. I met Inspector Lowes on No. 2 platform, and there I saw the tie-rod hanging down. I cannot quite say where it was hanging from or where it was broken, but it seemed to be a long piece, extending over more than one bay. I told Inspector Lowes that I thought it was dangerous, and that the mail train should not be allowed to run into No. 1 platform. I stood and watched the roof come down. The west end appeared to fall first and the sash bars opened. My impression was that the tie-rod was supported at the wall, and the remainder of it, from the point where it was broken, somewhere between the second and third stiffeners, was hanging down.

Benjamin Chaplin, bridge inspector of the engineer's department, states: The main tie-bar of the fallen principal has been cleared sufficiently since mid-day to-day, the 9th inst., to follow it throughout. It is broken in one place only, between the second and third vertical stiffeners from the west wall, about 12 to 14 inches from the third coupling, also counted from the west.

Evidence taken on 12th December, 1905.

Lewis Bacon, a workman on the roof of the Avenue Theatre, states: At 3.30 p.m. on December 5, I was on the crown of the roof of the Avenue Theatre close to the wall which separates the auditorium from the stage. I was in line with the second pier of the station wall from the south. At that time I heard a loud report like a gun going off. It appeared to come from the roof of the Charing Cross Station. It was an unusual sound, quite different from the noises that the workmen on the roof were making. On hearing the report, I turned round and saw a lot of men coming out on to the roof from the stages and running away. I could see the stages on which the men were working. Two or three minutes afterwards I noticed about a dozen men come back. They came back from the east side of the roof, and I saw them commence lashing up something, after getting through the openings in the roof on to the staging. It appeared to me that they were on the stage which was about half way up the west side of the roof, and under the glazed portion close to the second principal from the south. After looking at a drawing of the elevation of the main girder, it appears to me that they were in the third panel from the west. Immediately after the first loud report, I saw a portion of the crown of the roof, which seemed to me to be situated about 30 feet from the south end, appear to drop or sag inwards, and then stay in that position. I resumed my work, but on hearing fairly regular cracking noises from the roof, I looked again to see what was the cause, and then noticed that cracks were appearing in the relieving arch-work of the station wall which connects the two end pilasters. The cracks appeared to begin very close to the second pilaster from the south, and to run diagonally downwards and northwards. The appearance of these cracks made me think that there was some danger, so I called to my mate and went off the roof on to the temporary theatre scaffolding, which is south of the end of the station wall. I then saw the top of the second pillar from the south leaning outwards. I called the attention of the scaffolder to the appearance of this wall, but had scarcely done so before the roof fell in, and the wall of the station fell outwards on to the theatre. Where I was standing first was about on a level with the top of the station wall, and I therefore could not see the actual crown of the station roof. I was working on the roof of the theatre on the 4th December. Both on that day and on the 5th, I was frequently within about 20 ft. of the face of the west station wall. I did not notice during these days any cracks in the wall, or pilasters, or other signs of failure. If there had been any cracks in that portion of the station wall, which afterwards fell, it was so close to me that I think I should certainly have noticed them. I should say that about 10 minutes elapsed between the time I heard the sharp report and the collapse of the roof.

Robert Lane, scaffolder in the employ of Messrs. Patman and Fotheringham, contractors at the Avenue Theatre, states: At about half past three on the 5th December, I was on the temporary scaffolding at the south east corner of the Avenue Theatre. Where I was standing was actually south of the termination of the station wall. I heard a loud sound. It was an unusual sound. I did not know what direction it came from. The sound appeared to me as if it was iron or rivets breaking rather than a gun shot. I thought no more of the matter until the last witness called my attention to the condition of the station wall. When I looked I could see the top of the wall was 18 ins. out of plumb, leaning outwards. The bulge appeared first between the second and third pilasters from the south end. I then saw the mortar crumbling away, and I knew that the wall was falling. I stepped back and saw the roof crash down and the wall collapse. I had been working for Messrs. Patman and Fotheringham for 10 or 11 weeks at the theatre. I erected the scaffolding on the east side of the theatre close to the station wall which fell. The level of the scaffolding was considerably lower than the top of the station wall, but we were often quite close to the portion of the wall which subsequently fell. The wall appeared to be in thoroughly good order and condition. I saw no signs of cracks, or of its being out of plumb. I do not suppose it was any fault of the wall that the roof fell. I have never heard of any settlement in the wall of the theatre, or any part of the theatre before the accident occurred. There were some cracks due to an air flue which were of old standing, but they were not due to any settlement.

Edward Collins, foreman scaffolder with Messrs. Patman and Fotheringham, states: I have been employed at the Avenue Theatre for more than three months. I was responsible for the scaffolding all round the theatre. There was scaffolding between the theatre wall and the station wall. The top of the scaffolding is considerably below the level of the station wall. I was on the top of the scaffolding about 3.30 p.m. on the 5th December. I did not hear any unusual noise from the station, and I did not notice anything, until my friend (the last witness) called my attention to the condition of the station wall. When I looked at the wall it was bulging out like a balloon. This was just opposite the stage of the theatre. The bulge got bigger and bigger, and then it went all of a sudden. The second principal—counting from the south—fell first and a large piece of wall immediately under it fell. The end principal fell afterwards, and brought the remainder of the wall with it. I stood and watched it all fall, until the scaffolding—within a length of where I was standing—was down, and then I made for the ladder. I have had many opportunities of seeing the station wall since August last, and I have noticed nothing in its condition which would lead me to suppose it was unsafe. If there had been cracks of any importance or size in this wall I should have been sure to have seen them, and if I had seen them I should have called the attention of the contractors to them. It does not, therefore, appear as if it was any fault in the wall which brought the roof down. I never looked to see whether the wall was out of plumb.

Evidence taken on 15th December, 1905.

Harry Foster, labourer in the engineer's department of the Railway Company, states: On December 5th I was watchman on the platforms in Charing Cross Station. My instructions were to sound a horn in case of trains arriving, or passengers passing, under that portion of the roof where the workmen were engaged. The men stopped working at the sound of my horn. About 3.30 p.m. I was standing in the permanent way in No. 1 road at the south end of the station. I heard a loud noise as if something had fallen on to the temporary corrugated roofing of the platform. I thought something had fallen on the roof between Nos. 1 and 2 roads. I got up on the platform to see what had fallen, but seeing no signs of anything I looked up to the roof. I walked northwards and looked up to the roof. I saw the men on the stage in the third panel from the west looking at a broken bar. This bar was under the staging. Some of them were kneeling on the staging looking over, and others were looking through the staging. It appeared to me that this rod was hanging from the second coupling joint, and that it was broken off close to the third coupling. I warned Inspector Lowes to keep people on the platform away from this point under the roof. I also warned the shunter foreman and a gentleman who was seeing some passengers off. At that time I had not seen foreman Stirling on the stage. I then went south again round by the Custom House to see if there were any trains approaching or moving.

Then I went back to where Inspector Lowes was standing, and I saw Stirling come to the edge of the stage. He shouted out, "Watchman, stand clear." I then got into the permanent way of No. 3 road, and walked towards the signal-box in the middle road, with the red flag under my arm. I went there to watch for and stop any trains arriving, and to watch the signals. I kept watching the signals. All the running signals applying to Nos. 1 and 2 roads were at danger. I did not hear any noises coming from the roof after the first loud sound. There were a few things falling which I thought came from the staging. I next heard a great crash and saw the roof fall. I did not take any action for protecting Nos. 3 to 6 platforms because I thought the only danger was from this one bar falling on Nos. 1 and 2 platforms. I did not notice any further breaking away of the tie-rod from the coupling joints. I have been doing this watchman's work at Charing Cross Station since the work was commenced in last August. If I had seen any train approaching Nos. 1 or 2 roads I should have displayed my red flag and stopped it. I did not see anyone cleaning or doing anything to the advertisements on the west wall of the station.

George Coulson Stirling (recalled) states: Mr. Ellson was up in the roof on the day previous to its fall. He went up in the roof two or three times every week. I saw no signs of any movement in the walls or girders previous to the accident. I have not yet seen the fractured ends of the tie-rod. On the west side of the roof, between the first and second principals, all the glass was removed over the staging, that is to say, the glass over half the bay. On the east side there were four lines of panes of glass removed over the staging. This glass which had been taken out had been removed from the roof. The actual extent of lightening the roof amounted to four rows of glass on each side. The other glass would have been filled in before the stages were removed.

Edward Mercer, foreman bricklayer in the employ of the Company, states: I have occupied my present position for over 20 years in this district. I am well acquainted with the walls of Charing Cross Station. There are cracks of old standing in some of them. These are principally in the panels between the piers which support the principals. No fresh cracks have been observed in the walls during the last 20 years. There never have been to my knowledge any cracks in the pillars. All the cracks that I am aware of have "tell-tales" fixed, and these are measured several times in the year. There has been no growth of these cracks. There were none of these cracks in the two panels of the west wall that have fallen. One of the cracks that we now have under observation is in the third panel from the south in the east wall. I am not aware of any cracks in the last two panels to the south of the east wall. I have given my foreman, Hutchinson, special instructions frequently to examine the walls. He would report to me at once if anything were wrong with the walls. If there had been any movement out of plumb I should have noticed it and called the engineer's attention to it. There was nothing in the state of the walls or their foundations, in my opinion, which can explain the fall of the roof.

Henry Hutchinson, district foreman bricklayer, states: I have been employed by the Company as district foreman for about 23 years, and I have been well acquainted with the walls of Charing Cross Station all this time. I have had special instructions for the last 18 years to carefully watch the station walls. I generally walked round the station and looked at the walls once a day, sometimes twice. In the panels of the west wall that have fallen I never observed any cracks. In the viaduct sub-structure there were some cracks in the walls of the porters' room and guards' room. These were pointed some two years ago, and I have not since detected any movement prior to the fall of the roof. There have not been, in my knowledge, any cracks in the two south end panels of the east wall. There is an old crack in the arching under the tank. This joint was pointed up in October and has not moved since. If there had been any settlement of the foundations, I should have noticed cracks occurring. I do not see how the condition of the walls could in any way have caused the fall of the roof.

George Ellson, an assistant engineer in the service of the Company, states: I have been seven and a-half years in the service of the Company. In December 1902, I received instructions from the Company's chief engineer to examine and report upon the condition of Charing Cross Station roof generally, more especially with regard to the condition of the iron work. I had staging erected at various points where I thought the corrosive effect of smoke from the engines would be most likely to be seen. These stages were supported by chains and rods from the roof. The stages were very small. Such ironwork as it was possible to get at from these stages was examined. There were stages at four points. One of these stages was at No. 1 principal on the west side, another was at the seventh principal counting from the south, another at the ninth, and the last was on the east side at No. 4 principal. In addition to that we were lowered at three different points by cradles from the roof. Mr. Maddock, inspector of ironwork, and foreman Stirling, were with me. From the stages we examined all the sash bars, purlins, the main rib, the vertical struts, and diagonal pieces, and the main tie-rods that were within reach. The actual piece of tie-rod we examined in the first principal was the one in the second panel from the west. Generally speaking, we found the ironwork in good condition. It was rusted, the sharp corners having been mostly attacked by the rust. In all the tie-bars there was no serious diminution of metal. There was still a good deal of paint adhering to the original metal. The metal of slight section, such as three-eighths flat bars, had suffered most from corrosion, and the under-side of the "T" sash bars. There was no material loss of sectional area in any portion of the principals. I suppose that the reason for the sash bars suffering most was that the fumes of smoke would be prevented by the glass covering of the roof from getting out. The smoke would be hugging the underside of the glass, and therefore more constantly in contact with the sash bars, than with any other portion of the ironwork. The rusting that was going on was in the form of powder rather than flakes. The greater portion of the rust in my opinion was due to sulphur fumes rather than to moisture. The rusting of the "T" sash bars was also due to condensation from the roof. There was a great deal of paint adhering to all the ironwork. We did not observe that any bolts were missing, and found no evidence of weakness of any description. I have seen the tie-rod since it was fractured. There is not much paint left on it at the present time.

The outside of the rod is pitted with rust or corrosion. The marks are not of any depth. I do not suppose I could have detected the fault shown by the fracture, in the tie-rod, even if it had been turned in a lathe and polished, because it appears to me that the whole flaw was in existence when the roof was erected, and has always existed as it was found after the fall of the roof. My idea is that it is a fault which originated when the metal was piled and whilst it was being hammered. I do not think myself that the flaw has grown in any direction. I did not see any signs of drawing out of metal in the fracture. I should say the whole of the fracture had a crystalline appearance—there is no sign of fibre. I reported to Mr. Tempest that the ironwork generally was in good condition, that it required scraping and painting, and that some ironwork of slight section required renewal. It did not appear to have any signs of weakness. That was nearly three years ago. Previous to examining Charing Cross roof I had examined the Cannon Street Station roof. The condition of that roof was not so good as that of Charing Cross Station. I was put in charge of the repair work of Cannon Street Station roof in September, 1903, and I was in charge during the 18 months that the work was going on. I was put in charge of the repair work at Charing Cross Station at the beginning of July 1905. My instructions were to carry out the scraping, cleaning, and painting work (three coats of paint), and to put the roof in a thorough state of repair. Staging was constructed for the purpose carried by the purlins of the roof, and the men carried out the cleaning and painting work from the stages. I instructed Stirling that the work was to be done in a thorough manner. All the ironwork was to be examined, and I myself examined almost the whole of it as it was cleaned. I was up in the roof two or three times a week. I used to test the manner in which the ironwork was cleaned by scraping off the paint in places, after it had been put on, to see if the rust had been removed, and the proper number of coats put on. I calculated out what the effect of the additional weights brought on the roof would be. To do this I took out the actual weights of the stages, allowed for a horizontal wind pressure of 40 lbs. per square foot and 5 lbs. for snow. I calculated that the total results of these loads would be a maximum tension of seven tons on the square inch of the tie-rod. With the available sectional area of 16 inches this would mean a tensional pull of about 112 tons on the tie-rod which broke. This would allow a factor of safety of about three. I told Stirling, who was in charge of the work, that nothing but what was necessary was to be stacked on the roof of the station. I think the material which he, in his evidence, states was on the roof was in excess of what actually need have been there. I have found Stirling a very careful man. I am quite sure he would not have removed any bolts or nuts, or any integral part of the roof without obtaining my permission. I also think he would not have stacked the zinc and glass on the roof unless he thought it necessary for keeping the work going. I was on the roof on the day before the accident. I did not notice any material stacked on the roof then. I thought then he was keeping his stages very clear of weight. I noticed certain cracks in the brickwork panels between the pilasters at the south end of the station on both sides. I ascertained from Mercer that the cracks were of old standing. The walls did not show any signs of weakness. I do not think that the fall of the roof was occasioned by any subsidence of the foundations of the walls. I am not aware of any unusual vibrations being set up in the station. If there had been any bolts missing in the portion of the roof when I first examined it, in 1902, I should have seen the holes and found it out. I thought at that time that the coupling joint between two tie-rods was formed by the collar, and that the collar and flat iron above it was one solid forging. Since the roof fell we have found that this is not the case, and that there is a straight joint between the collar and the flat iron above it to which the diagonal braces and verticals are riveted. I should like to add that my opinion of the flaw in the tie-rod was founded upon a cursory examination only.

Evidence taken on 8th February, 1906.

Mr. Percy Crosland Tempest, M.I.C.E., states: I am chief engineer of the Managing Committee of the South-Eastern and Chatham Railway Companies, and as such am primarily responsible for all engineering structures. I have known Charing Cross Station for 25 years, and have had charge of it from 1895. I had charge of it from 1895 to 1899 as resident engineer, and from 1899 onwards as chief engineer. The station roof was designed by the late Sir John Hawkshaw, and was completed about the year 1863. It was built by an independent company which was amalgamated with the South-Eastern Railway Company in 1864. The station is vested in the South-Eastern Railway Company and managed by the Managing Committee. The type of roof is a crescent trussed bow string, supported on side walls. The length covered by the roof before the collapse was 510 feet, and the clear span between walls is 164 feet. There are 14 main principals and one screen girder at the south end. The distance from the wind screen to the first principal north is 41 feet 6 inches. The width between the first and second principals is 37 feet, between the second and third 36 feet, and the remainder are 35 feet apart. These dimensions are central. Each principal is carried on pilasters which rest on a brick viaduct. The side walls between the pilasters are filled in with brickwork in mortar. I put in a plan showing the dimensions of the brickwork and the heights. It is 45 feet from the top of the side walls to the level of the crown of the roof, the maximum depth of the truss being 20 feet. The end screen consisted of a box girder with an ordinary built up plate flange for the bottom member, tie-rods not being used. The ends of this girder rested on the two southern pilasters, and were placed at the same level as the footings of the main principals. The width of the box girder was 3 feet. It was not stayed in any direction southward. The ironwork was constructed by Messrs. Cochrane, Grove, & Co., and the iron came from Lord Dudley's works. At the south-east end of the station there are buttresses which support a tank. I have no reason to believe that they were built for any other purpose than to carry the tank, but they add considerably to the stability of the wall at that point. There are no buttresses at other portions of the wall. The buttressing of the south-east end was carried out at the time of the construction. The main rib which collapsed weighed 17·26 tons. Including the weight of the rib, the portion of the roof carried by the principal which fell weighed 63·16 tons, or 18·4 lbs. per superficial foot, the actual area of roof supported by this principal being 200 feet by 38·6 feet, or 7,700 superficial feet. To this must be added the staging supported by it, which weighed 17·41 tons. Therefore, the total dead load carried by this principal prior to its failure was 80·57 tons, or 23·4 lbs. per superficial foot of roof area. The design of the roof is that of a contained arch. There is no thrust on the walls, the pressure being vertical. The scantlings of the different members of the principal which fell were: purlins, four angle-irons, $3\frac{1}{2}$ ins. × 3 ins. × $\frac{1}{2}$ in., purlin lattice bars, 2 ins. × $\frac{3}{8}$ in., purlin bracings or common rafters, two tee-irons, 5 ins. × 3 ins. × $\frac{3}{8}$ in., lattice bars of the common rafters, 2 ins. × $\frac{3}{8}$ in.; main rib, top boom, four angle-irons, 6 ins. × 3 ins. × $\frac{3}{4}$ in., web plates of main rib, 18 ins. × $\frac{1}{2}$ in.; tie-rods, middle bay $4\frac{1}{4}$ inches diameter, next bay $4\frac{3}{8}$ inches, next bay $4\frac{1}{2}$ inches, next bay $4\frac{3}{4}$ inches, and the side bays 5 inches; panel counter bracings, flat bars, 4 ins. × $\frac{3}{4}$ in.; panel verticals, two tee-irons, 6 ins. × 3 ins. × $\frac{1}{2}$ in. I hand in three diagrams showing the stresses (1) due to weight of roof only, (2) due to roof and staging, viz., 80·57 tons, equivalent to 23·4 lbs. per super. foot, and (3) the stresses on a normal principal with the central interval of 35 feet, which would result from the test load of 127 tons distributed, which was applied at the works before erection. This latter weight is equivalent to a load of 40·7 lbs. per square foot of roof area supported. The additional weight carried by the principal which fell owing to the staging was 17·41 tons, including men, tools, canvas sheets, and zinc, &c. The staging, with the exception of that under the lantern, weighed actually 27·43 tons. This includes everything, men, tools, and materials. From this amount a deduction of ·8 ton must be made on account of the glass which it was necessary to remove before the hangers could be put up. The main stage therefore weighed 26·63 tons. The centre stage under the lantern weighed 5·38 tons. Therefore, the total additional weight on the roof due to staging, materials, men, &c., was about 32 tons. To arrive at the weight carried by the principal which fell, I resolved the weights according to the points at which they were carried by the hangers, and this gives a load of 17·41 tons of staging carried by No. 1 principal. From the diagram of stresses which I have handed in it will be seen that on the tie-bar which broke the stress in tension amounted to $81\frac{1}{2}$ tons. The area of the bar as erected was 15·9 square inches. Therefore, the stress in tension per square inch of the whole area was 5·13 tons. The weight of staging carried by the principal at the time of its collapse amounted to approximately 5 lbs. per square foot of roof area. The factor of safety in the tie-bar which broke, assuming an ultimate strength in tension of 20 tons per square inch, was therefore 3·89. A similar staging was put up eight years ago, and the stresses therefore would be identical at that time. Considerably heavier weight in the shape of staging was placed on the roof about 37 years ago, after a fire on the station platform. I have calculated that a horizontal wind pressure of 40 lbs. per square foot, in addition to the dead weight of the roof, would bring a tension stress on the tie-bar in question of 5·71 tons per square inch. I have also calculated that a horizontal wind pressure of 27 lbs. per square foot would give the same additional stress in tension on the bar as that due to the staging. As regards inspection, there are no fixed periodical inspections, but the roof is constantly under observation—both the roof and walls. There are always men working on the roof. They were practically there every week, and they had instructions to examine wherever possible, and report anything they noticed to be wrong with it. The walls were walked round daily by the foreman bricklayer in charge of the London district, and any movement would have been at once reported. The district engineer also visited the roof twice a year. It was an examination made in the best possible way without a staging. When the roof is painted and scraped, it is very carefully examined, and in addition there is one special inspection made between the periods of repainting. The last renovation was completed in February, 1898. I was then in charge of all the works of the South-Eastern Railway as resident engineer. In December, 1902, I ordered a special examination to be made by an engineer, Mr. Ellson. He reported verbally to me, and we spent the best part of a day going through his note book and observations. His report was that the condition of the roof was generally satisfactory, that the principals were in very good order, but that some of the light iron work, for instance, the glazing bars, and the intermediate rafters, were showing signs of slight corrosion. After carefully considering the whole report, I came to the conclusion that I would renew the glazing bars which were rusted and the common rafters, when the roof was painted, but that it would not be necessary to do anything to the roof at that time. It was suggested by the directors in 1905 that it might be advisable to remove the roof altogether, and I was requested to look into the question of cost. They suggested that it might with advantage be removed because it was architecturally a blot upon the City of London, and expensive to maintain. I, however, advised them to retain the roof as it was in such good condition. I thought it would be a waste of money to remove it. To my knowledge there had been no repair work done to the roof up to 1905, except as regards the lantern roof. The work carried out from time to time had consisted of scraping, cleaning and painting. There have not, therefore, been any records kept, as there was nothing to keep records of. There have been cracks in the walls ever since I have known the station. These have been under close observation, and tell-tales have been fixed upon them, but no movements have been recorded. Subsidences of the foundations of the viaduct would be shown by cracks in the piers or arch work of the viaduct. There have been no fresh cracks of recent years. I cannot find that there is any ground for the supposition that the collapse was due to failure or subsidence of the foundations or walls. As regards the work in connection with the Baker Street and Waterloo Tube, and the connections between that tube and the District Railway, if there had been any settlement caused by these works it must have shown itself first of all in the viaduct upon which the walls are built, and also in the walls themselves. The only work in or near the station that has been going on is the repair to the main girders at the fan end of the bridge, which has been in hand for the last 15 months. There has been no piling or anything to cause vibration. I do not consider that the scorching of the paint work, which was the only result of the fire that occurred in 1868, would have had the likelihood of weakening any of the members of the principals. The building that actually was burnt on that occasion was the Continental shed on the No. 1 platform, which is 60 feet below the principal. As regards the repair work which was being carried out on the roof immediately before its collapse, I was removing some of the glazing bars and some of the common rafters. I was not taking them out because they were weak, but because they were rusting. I have had the worst of these which had been removed tested. I find an ample margin of strength left in them, and they would have done duty for a great number of years. I think there is only one possible theory to account for the collapse of the roof. The tie-rod which broke showed a bad flaw caused, as subsequent examination has demonstrated, by an imperfect weld, and it is not necessary in my opinion to look further for the cause of the collapse, although I have considered it from every other possible point. The different lengths of the tie-rods, which are about 18 feet long, have screwed ends which are fitted into muff couplings situated at the bottom of each of the vertical members of the truss. From careful examination in the testing room of other ends of similar bars, it is fair to assume that these screwed ends have been attached to the main body of the tie-bar by a scarf weld, and it was one of these welds which gave way. The fractured section revealed the fact that only a small proportion of the area of the metal of the bar had been doing its work, and that is a complete explanation of its failure. It is very difficult to say how much of the metal was actually in contact in this rod at the time of the collapse, but speaking roughly I should say a little more than one-third of the bar was doing work. This would reduce the available section to between five and six inches. The weld was in no way affected by rust or corrosion. The loss of diameter in the tie-bar due to rust was one-tenth of an inch, so that the tie rod instead of being $4\frac{1}{2}$ inches in diameter, as when erected, had at the time of failure a mean diameter of 4·4 inches. The bar in question was not truly circular. There is nothing to show that there has been any fatigue or change of structure in the material away from the weld. The metal in the bar behind the fracture, when tested, showed an ultimate strength of about 20 tons to the square inch in tension. The fracture shows that over its area the iron was in metallic contact at isolated points round the circumference but not in the centre. The only practical method that is available for the examination of iron work in a roof is by scraping the surface clean and then examining it. If any signs had been noticed of a fracture appearing, the place would have been examined by an engineer. I do not think it would be a practical test to pass an electric current or currents through the bar, nor would it have revealed the presence of this flaw, which I am quite sure could not have been detected. Paint is cleaned off by using flares and wire brushes. The principal that fell is, generally speaking, about in the line and over where the locomotives stand in the station, and therefore it was more liable to corrosion or rust than, possibly, the others were; but, in spite of this, the members were in very good condition. I have every confidence in Mr. Ellson, the assistant engineer, and Mr. Stirling, the bridge foreman, who was in charge of the repair and painting work. I am quite sure nothing was visible on the surface of the tie-bar to show that the bad weld was in existence, and I do not, therefore, think that when they had come to this tie-bar in the ordinary course of their work, and had scraped and cleaned it, they would have observed the flaw. Foreman Stirling had no idea when he saw the broken brace that the tie-rod was also broken, as it was hidden from his view by the stage and sheeting; had he realized this he would certainly not have recalled the men, to endeavour to repair the bracing, as he did. He is a good practical and reliable workman, but of course he does not understand the theory of roof strains. When it was decided to repair and re-paint the roof, I carefully considered the best means for protecting the lives of the men at work, and preventing any possible danger to passengers on the platforms. The materials provided were new, the stage was close boarded, sailcloth was provided under the stage in case any men should lose their footing, a temporary corrugated covering was put over the platforms, under that portion of the roof which was under repair, for the protection of the passengers, and a watchman was provided on the platform in communication with a man on the stage. This latter arrangement came into operation when the work was commenced, and it would have continued throughout the whole work. It was no doubt due to this that the deplorable loss of life was not greater, as the platform watchman had the people cleared away. I do not think that railway engineers of the present day would erect a roof of this character, because it is so expensive to maintain, and the greater cost far outweighs any advantage of clearing the supports away; and, if erected, it would have duplicate tie-rods. We are repairing the roof at Victoria Station at the present time, and there the rod has more than one member. As regards Charing Cross roof, the directors have decided to remove it entirely, and for this purpose a staging is now being erected. It will be replaced by a ridge and furrow roof, supported by girders extending from side wall to side wall with two lines of intermediate supports erected on the platforms. This will enable the present walls to be considerably reduced in height and will do away with the possibility of any side thrusts upon them in future. Until the whole of the old principals are removed the existing tie-rods will be made quite safe by the additional help of steel wire ropes to supplement their strength. There had been no wind in the vicinity of Charing Cross of any force for fully a week before the accident. About a fortnight previous half a gale had been blowing for several hours. There is no wind bracing in the roof structure. The resistance of each wall (per $38\frac{1}{2}$ ft. bay) to overturning is, I calculate, equal to about $4\frac{3}{4}$ tons applied horizontally at the bedstones. This does not take into consideration the adhesion of cement or mortar. The whole of the walls could never be exposed to the force of the wind, as they are largely protected by the surrounding buildings. The expansion arrangements do not appear to have worked, and any expansion or contraction of the roof must have been taken up by the walls. I was not aware—until some time after the accident—that the screwed ends of the tie-rods were welded to the bars. It was only after following the experiments at Messrs. Kirkaldy's works that this was demonstrated. As regards Cannon Street Station—although the design is generally similar—there is a much greater margin of strength. The walls are 50 per cent. thicker, and the truss members as much stronger than in the case of Charing Cross.

Mr. William George Kirkaldy states: I received first the west end fracture of the tie-bar, and afterwards also the east fracture with a moving coupling attached. I was asked to make examination tests. First, I examined the bright fracture. It had to me every appearance of a weld, and of being defective in the centre part. There is a trace of cinder in the very centre of the fracture. I felt that although it had all the appearance of a weld I must keep an open mind and endeavour to prove conclusively that it was a weld. There was, perhaps, I thought, some other explanation of it. The line of fracture is at a blunt angle and that is one of the reasons why I considered it likely to be a weld. I cut off the bright fractured bar about an inch behind the actual point of fracture, I then took a piece off the stump end that was left and treated it with acid. This showed to me the method of manufacturing the bar. There were eight slabs of iron piled one on top of the other. This constituted the bar itself. On the face of my cut nearest the fracture I found, after treating it with acid, there was a disturbance in the layers of iron which made the bar, and it appeared as if this was a continuation of the line of what I considered was the weld. This disturbance was not visible at cut No. 2, which simply showed the marks due to the piling of the rod. The disturbance shown on the cut nearest the fracture strengthened my idea that the fracture had taken place actually at the weld. I still had to bear in mind that although this was evidently a weld it might not have been an intentional weld. I thought that if it had been an intentional weld I should find traces of a similar weld at the other end of the bar near the coupling; on the other hand, if it was only a chance weld the other end of the bar would not show any sign of welding. The result of my first careful examination of the exterior of the other end of the bar was that I could find no sign of any weld. Then I cut off about 20 inches of the bar, and turned a portion of it in a lathe. After reducing the diameter in the lathe considerably, I found distinct traces of a weld. The result of this examination in a lathe was to prove to me that the bar was of set purpose welded at both ends. I thought it was quite possible for the smith to have set up both ends of the bar from the solid for the screw ends, but having found welds at both ends I thought it was clear that owing to the length of the bar, about 18 feet, it was not possible in those days to turn the bar in a lathe, and that for that reason the screw ends were first of all manufactured, and these ends then welded on to the bar. When I had an opportunity, before making these tests, of seeing the iron work that had fallen, I examined several of the bars very carefully, but could find no signs of any weld on any of them, and this was the reason that, though I had made up my mind that the actual fracture was at a weld, I was concerned to find out whether it was a chance weld or an intentional one. I obtained from the engineer of the company several additional bars with which to continue my investigations. In the case of the three bars that I examined, by scraping off the rust down to the clean surface of the metal, I found at one end only of each of the bars traces of a weld. The marks were 1 inch to 1½ inches in length and had the appearance of a raised fibre on the surface. In no case was there anything of a crack at the weld. I failed altogether to get any trace of a weld at the other end of each of these bars. I turned off a portion of the metal in a lathe, and I then found the mark of a weld on the bright surface of the metal that was exposed by the tool, but in no case was there any visible crack or cavity. The result of the examinations that I made of these bars clearly proved to me that they all had welds at each end. Possibly, therefore, it is a fair inference that all the other tie-bars in the roof were similarly manufactured, for until I had examined these other bars there was always the possibility that the welds in this fractured bar were due to chance only. Looking at the west fractured end of the bar, the clear crystalline portion was solid at the time of fracture. This bright metallic surface was approximately the upper side of the bar in position. I think, that in addition to the bright surface, the remainder of the discoloured surface round the circumference was at some time or other also in contact and adhering. I gather this from the fact that this discoloured portion has still a sharp grain when touched, and in addition to this you can see spots here and there on the circumference and nearer the centre of a metallic brightness. The actual centre of the bar has a different appearance and has evidently never been in contact. This portion is defined by the ash which surrounds the core, and the core itself has a smooth undulating surface with a fire skin on it. The iron of which the bar was made may be described as good quality iron. I cut out two round iron test bars from the bar that broke, about 6 inches behind the fracture, and tested these for tension. These two bars broke under an approximate tensile stress of about 20·6 tons per square inch. The contraction of area in each case was over 40 per cent. The solid portion of the bars had all the character of new iron. There was no sign of any deformation or deterioration due to fatigue. The result of a number of measurements of the circumference of the bar that broke, showed that 4·4 inches would represent the mean diameter. The waste due to rust or corrosion amounted therefore to one-tenth of an inch on the mean diameter. I made other tests of the metal surrounding the weld at the other end of the broken bar, and found generally the same results—namely, high tensile strength in the solid portions, and nearer the centre, where the welding was less perfect, the tensile strength diminished, until quite in the centre where the cavity existed there was no tensile strength. I tested two other tie-bars after reducing the areas in a lathe to 8 square inches, and found that the breaking tensile strength of these two specimens, each of which contained a weld, was 11·15 and 12 tons respectively on the square inch. In these two cases there were similar pockets to those found in the tie-bar which broke. Two other specimens, also amounting to 8 square inches of the central portion of the bar, broke at 14·1 and 17·3 tons per square inch respectively. The fracture in these cases was also through the weld. In these four cases the metal that was turned off in the lathe to reduce the area of the bar was in each instance sound and good. I do not think any heat such as would be necessary to burn off paint would have any deteriorating effect upon the quality of the iron of the tie-rods. I think that the centre portion of this tie-rod was never in contact. I am sure that if the outside of the bar had been scraped clean, it would have been impossible to detect the bad flaw when it was in position in the roof. I could discover none of the places where the rods had been welded in my laboratory until some of the metal had been turned off in a lathe, and then there was only the indication afforded by the shadow on the metallic surface. I do not think it would have been possible to discover the bad weld in the fractured rod by tapping. If the bars had been sent to me for examination and general report I should have said they were in excellent condition as regards welding. By this I mean I should not have known there were welds in the bars. The examination that I made of the broken tie-bar, and of the others which were subsequently received by me, was one that it was quite impossible to have made in the roof. I am quite certain that if I had been called upon to examine this particular broken tie-rod before it snapped, and as it was placed in the roof, I should not have been able to discover that there was anything to be suspicious of. I should not have found any crack or opening on the surface. The development of the flaw has occurred from the interior and not from the exterior.

Evidence taken on the 16th February, 1906.

Sir John Wolfe Barry states: I was consulted by the Managing Committee of the South Eastern and Chatham Railway Companies about 24 hours after the roof fell in, in conjunction with Sir Benjamin Baker. I was a pupil and assistant to Sir John Hawkshaw, and I was stationed on the work, under the resident engineer, whose name was Stanton, when the roof was being erected. That was in 1863, or thereabouts. I saw the roof put up, but I did not see it manufactured. Sir John Hawkshaw was responsible for the design of the roof. Messrs. Cochrane, Grove and Company were the contractors for the iron work. The iron was made at Lord Dudley's works. The whole of the metal was wrought malleable iron. I went down to Messrs. Cochrane and Company's works, more as a visitor than anything else, on April 13th, 1863. I kept notes of what I saw there. One of the principals was fully constructed—I cannot tell which, but my impression is that the station roof was erected from the river towards the land, and therefore it would probably be one of the earlier principals about to be erected. Without stating it as a fact, I think it is reasonably probable that it must have been one of those principals that was near the wind screen, and it might have been the one that fell. The principal was erected at the contractor's works on a sort of timber staging where all the deflections could be measured, and it was supported laterally. Pig-iron was applied at different points, particulars of which appear in the diagram I have in my book here. That diagram was made in 1863. Looking at the drawing in my note book I find that the tie-rods have not the same dimensions as those of the principal which fell. Starting from the wall, the size is $4\frac{11}{16}$th, in the next bay $4\frac{1}{2}$, in the next $4\frac{3}{8}$, in the next $4\frac{3}{16}$th, and in the middle bay $4\frac{3}{16}$th. The first test put on was 26 tons, distributed at the various verticals. The deflections were then taken with this load of 26 tons, which was in addition to the weight of the principal itself. I have a note in my book that the approximate weight of the truss was about 22 tons. The next test was to increase the 26 tons to 50 tons, and all the deflections were again taken, then the weight was increased to 70 tons and all the deflections taken, then to 90 tons, and afterwards to 105 tons, all the deflections being taken each time. The weight of 40 lbs. to the square foot of superficial area carried by the principal would be equal to a total of 125 tons. After these tests had been made the load was all removed, and 10 tons was suspended between the centre and one end, and $52\frac{1}{2}$ tons distributed on the other half of the span and the deflections taken. Next, the load was wholly removed with the exception of 50 tons and the deflections again taken, and afterwards the whole of the load was removed and the deflections taken again. The greatest permanent set appears to have been at the centre of the arch, and amounted to ·74 of an inch, and the total elongation was ·49 of an inch at one end. I have no knowledge at all of the calculations for the design, but from the notes I took during the visit I have referred to, the total load of 40 lbs. per superficial foot appears to have been taken into account in the design of the roof; this would be inclusive of the weight of the girder itself. At the time the rod broke it now appears that there was about 65 per cent. of this test load of 127 tons on the principal. I was present when the west end of the broken tie-rod was uncovered after the collapse. I was one of the first who saw it. There cannot be the slightest doubt, I think, that there was a most important flaw in that rod where the fracture occurred. The exact dimensions I dare say you already have, but my impression is that the flaw extended over something like two-thirds of the area of the section of metal. Roughly speaking, about 5 or 6 square inches of metal would be doing work at the time the rod broke. In addition to the large bright area of the fracture, there were one or two small islands, as it were, of bright metal, where the adherence had only just been broken, and there were also similar places in the circumference. I do not think there was likely to be any sign of a fracture on the outside of the tie-rod. The mere fact of the existence of those islands shows indubitably that the fractured surfaces must have been adhering more or less all round the circumference. It was not a gaping wound. The metal was held together where the larger amount of bright metal was, and also where the islands were, so I do not think there was any reasonable probability that anything was showing on the exterior. I do not think that anything would have been seen on the outside even if the iron had been scraped and got ready for re-painting. In my opinion this large flaw could not have been discovered by sound or the hammer. The contact was evidently very close indeed. I have no knowledge of the means used in ironworks for testing welds of this size, as I have not come across them in my practice. I am confident a great deal of care was taken with this roof when it was erected. The contractors were at that time supposed to be at the very head of their business. They had put up some of the largest roofs that had been erected. For instance, the big roof at New Street Station, Birmingham, was built by them. The quality of Lord Dudley's iron, too, was supposed to be as good as could be got for this sort of purpose. I cannot help thinking that the flaw must have grown. It is obvious, I think, by the look of the section that the metal always had a very considerable flaw in it. I do not think that contact was ever made in the centre of the weld. I think that growth of a flaw like this must occur when you get a severe strain on the rod. You then have a condition of things where a gradual growth of a flaw could continue, and in this particular instance the part of the metal which was adhering must have been exposed to a very severe strain. In the most ordinary conditions of wind, this particular rod must have been exposed to very high strains indeed on the part that was adhering, and it must be remembered that there was a gale of wind, which was quite remarkable, within ten days of this accident. It is such a large flaw that I should hardly think it could at first have been so bad as it turned out to be, but it is very difficult to form an opinion after a flaw has been extending for some years, because you get some discolouration from steam or moisture. It was more likely to have grown from the centre outwards. I think there can be no doubt that originally the worst place was in the centre. I do not think that more frequent painting of the bars would have prevented the growth of a flaw of this description. I do not see how more frequent painting could have reduced the tendency of the flaw to increase. The tendency to increase was due to very heavy and abnormal strains on the portion of the metal actually adhering. I do not think any protection from the steam or fumes coming from locomotives standing under the roof would have decreased the liability of this flaw to enlarge. Unfortunately, almost everybody is dead who had anything to do with the putting up of the roof. It has been proved that the flaw occurred at a weld, and it appears from Mr. Kirkaldy's experiments that welds existed at each end of the tie-rod. The design of the roof was in accordance with the best ideas of engineers in those days. I see no objection to the design of a contained arch at the present time, but there would be many alterations in details. I do not see any objection to a roof standing on a wall of the thickness of these at Charing Cross, except for a sideways pressure of wind. The walls appear to have been strong enough for all vertical weight, and they were not designed to carry anything but vertical weight. I remember an instance that arose after the roof was erected regarding wind pressure. The tank house at the south-east end of the station, where there are buttresses, was erected not only with the idea of providing a tank house, but with the intention of strengthening the walls against south-west winds. The fixed end of the principal was at the east side, and the south-east winds not being so strong as those from the south-west, it was not thought necessary to buttress the south-west wall in the same manner. It must also be remembered that in those days there were no high buildings surrounding the station as there are at the present time. Nowadays, one would not design a roof of this size with single bars which had been welded. In the present methods of manufacture I do not think that welds would be used at all. As to the removal of the roof, we agreed that under all the circumstances it would be better to replace it by another, but the circumstances were not all connected with this accident. Other considerations, which weighed very much in my opinion, are that the whole roof is nearly 50 years old, and that repairs to it would become more and more serious as time goes on from natural corrosion, and so on. Further, my opinion was that it was only a question of time when this roof must come down from another reason which had been before the Board of Directors, from my own knowledge, for 10 or 15 years—that is, the enlargement of the station. When that takes place the roof would be in the way; it would interfere with the utilisation of the area, and generally it would be a perfect nuisance in the case of the enlargement of the station. Taking all these things into consideration, and not neglecting altogether the question of this accident, it seemed to me that the wiser course would be to pull the roof down. It would have been quite possible to have strengthened the ties in some manner if we had thought that there were no other reasons for taking the roof down. I carefully examined the piers of the viaduct after the accident, and I could not detect the slightest evidence of any subsidence. Therefore, I think the question of subsidence may be entirely put on one side. As for deformation under ordinary strain, I think it is quite unnecessary to look for such an explanation of the collapse when we have a cause which is amply sufficient to account for the fall of the roof. I do not believe that if the bar had been inspected as often as once a week it would have been possible to find out that the weld was in a dangerous condition. The value of a weld in a bar of this description depends entirely upon the workmanship. Speaking generally, the welding of a bar of this size is avoided nowadays. My impression is that the tie-bars in the principals of this roof were tested before they were placed in situ. My reason for this impression is the fact that Mr. Phillips, who was the contractor's managing engineer, erected a similar roof at New Street, Birmingham, some two years before. Mr. Phillips, in a paper which he read at the Institution of Civil Engineers shortly afterwards, stated that the tie-bars of the New Street Station roof were individually tested at the manufacturers' works before their erection in the roof, and I think it only reasonable to suppose that the same practice was adopted in reference to the tie-bars in the Charing Cross roof.

Sir Benjamin Baker states: I watched the erection of the Charing Cross roof as a young engineer interested in iron work and stresses, and I made calculations of the stresses. At the time, I was designing a contained arch roof for the Victoria Station, not the one which is now standing, but one that was contemplated at that time with a very much larger span. I was aware then that the Charing Cross roof was calculated for a load of 40 lbs. to the square foot, which was the basis for calculation taken by architects, I daresay 50 years before, in dealing with timber roofs. This figure included wind, snow, and the weight of the structure. The round figure of 40 lbs. was first fixed by Telford nearly a hundred years ago. I was aware that with the estimated load of 40 lbs. to the square foot, including the weight of the structure, the stresses (under that occasional and exceptional load) would fall within the limit of elasticity of the iron—that is, at the cost of no permanent deformation from stretching. That would not be good enough according to present practice, but in those days it was considered that, provided you did not have permanent deformation, the application of such a load as 40 lbs. to the square foot would be the sort of thing that would happen once perhaps in 20 years. It is different now. If you have ironwork subject to very rapid and repeated application of this load of course the thing would go to pieces under stress of this intensity in a few days. The Charing Cross roof was modelled in every respect upon the lines of the Birmingham roof, which three or four years previously had been submitted to the criticism of all the leading members of the profession at the Institution of Civil Engineers. There was not a suggestion in the discussion that there was anything wrong about the design either as regards principals or intensity of stress. It was known perfectly well that a stress of 9 tons per square inch might come upon the tie bars in a hurricane, or something equivalent to that. I do not think it ever has. In fact, I am certain it never has or the walls would have been blown down. I might say while on the subject of stresses, that the old Hammersmith Bridge, when the University boat race was on, was crowded with thousands of the public, and when they were on it the stress on the welded links of the suspension bridge was between 8 and 9 tons. Those links were all of iron, and they had welded ends. When that bridge was pulled down I bought a quantity of the chain work to use for temporary work on the Forth Bridge, so I had a good opportunity of seeing what the links were like after being in use 40 or 50 years. Although they were subjected to that high stress they had not in the least deteriorated as regards the quality of the metal. As to the quality of the metal, there is nothing in this to account for the failure of the tie-bar. I was consulted by telephone when the accident happened, and I was on the spot within about 20 minutes, I suppose. The fall of the roof was due to the fracture of a tie-bar, and that fracture arose from an invisible flaw which existed in the bar from the beginning. I saw the two ends of the broken tie rod. They showed the characteristic fracture of a welded bar which had had what is technically known as a pocket in the weld. I have seen hundreds of broken welded bars, and you can easily understand that when a flaw is in a bar, and the bar has passed investigation, it follows that the flaw must be invisible—that is, that it is in the centre of the bar. In making a scarf weld, such as this was, you have to be very careful to heat the iron to the proper heat, and not to overheat it, and then you have to get it in contact and hammer at it before the atmosphere has had time to form a scale on the surface. Borax and certain kinds of sand are thrown over the surface in order to make a sort of glaze or slag so as to protect it from the atmosphere. That is a difficult thing to do. The larger the bar the more difficult it is to get it exactly right, and sometimes you do not get metallic contact in the centre of the bar, but what is known to blacksmiths and others as a pocket occurs, in which a little of the slag is welded up all round. There is no difficulty in making a weld at the exterior because the blacksmith can see what he is doing there. The only way of finding out whether there is a pocket in a bar is by testing the bar as you know is done with every chain cable. Every link in a cable is examined very carefully to see that the weld is perfect so far as the outside is concerned, and the way of finding out whether it is sound in the inside is by testing it under quiet conditions. If that is done, when the stress is put on, you hear a little noise sometimes. That noise is a signification to you that there is an extension of some internal flaw. That is the only way I know of detecting an internal flaw. At the Arsenal, where there are very heavy forgings, every attempt is made to find out by magnetism whether there are any flaws. I have seen the use of the mariner's compass in this connection, but it is just about as much good as the use of the divining rod for water. It is tried in some works, but I do not think anybody believes in it. I have heard snaps from forgings when in a lathe. They go off like pistol shots without anything showing on the surface. I have not the slightest doubt there was a flaw here in the middle of the bar, and that the bar was absolutely sound on the outside. The extension of the flaw, such as it was, was from the interior towards the circumference, and directly it got to the circumference, the bar would snap and down would come the roof. You must not assume that because there was one third of the sectional area left there was one third of the strength. Looking at the bar, I should say it would be nearer one fifth than one third of the strength because the pull is not applied at the centre of gravity of the acting metal. Therefore, the stress is not spread uniformly. The size of the original pocket in the bar would amount to a circle of one and a-half inches or more in diameter, in which there was no metallic union whatever. Surrounding this pocket there would be a neutral zone of metal and dirt. Round the circumference of the bar there would be perfectly sound metallic contact. My experience is that in welded bars that is the normal condition leading to fracture. I knew Mr. Joseph Phillips very well, and I had such regard for his capacity as the most experienced iron-work man of the day that I got him associated with others as contractors for the Forth bridge. I have not the slightest doubt in my own mind, knowing Mr. Phillips, knowing Sir John Hawkshaw, and knowing what was done in the case of the Birmingham roof, that the same course that was followed at Birmingham was followed here, and that every bar and coupling was tested hydraulically before it was put up. It would be a test of nine tons to the square inch. I have looked into Mr. Phillips' note books, but I have failed to find anything about the testing of the Charing Cross roof. I am not astonished at that because it goes without saying that as he had done it before he would not think of mentioning it again. It is a very simple process to carry out this testing. In the case of cables, the Government test is nine tons to the square inch. Judging from what was done by the same men at Birmingham, I have no doubt that every possible precaution was taken for testing the Charing Cross roof. If this be the case, it is absolutely clear that the flaw must have increased in size from the time it was put up, or it would not have stood anything like nine tons to the square inch, which would have amounted to a total pull of 144 tons. I might say that we should not weld bars of this size nowadays. They would be made of steel, as a matter of fact. Now as to the reason why a flaw increases. Theoretically, if you get an initial crack the stress is infinite at the bottom of it. If the material were perfectly elastic in a scientific sense there is an infinite strain in the molecules at the bottom of the crack. The material is not, luckily, perfect, and so there is not an infinite stress, but a very heavy stress which causes tearing. There is a higher stress at the bottom of the crack than at any other part, and the result is that it goes gradually atom by atom. I know of absolutely nothing in the way of settlement of the walls, or the effects of fumes or oxidation, that was likely to have brought about this increase in the flaw. As regards settlement, this would first of all cause the cracking of the viaduct, because the roof rests on the walls and the walls on the viaduct. The viaduct shows no cracks such as would be caused by settlement. If the viaduct were cracked, it would put an extra pull on the tie, but the wall is 45 feet high and only about three feet six inches thick. If the viaduct had cracked and settled the result would be, not that the wall would have broken the tie, but that the tie would have held on to the wall and prevented it from tilting. It is like breaking anything with a fishing rod—like throwing a man down with a fishing rod. In this case all you would do would be to bend the rod, and all you would do here would be to bend the wall. We know, as a matter of fact, that these walls did from natural elasticity move backwards and forwards with the changing conditions of the weather. Although it was made very easy for the roof to expand and contract by putting one end of it in a swing, and letting it rock and swing, it proved in practice that it was still easier to rock the wall, and so the suggestion that a settlement of the ground brought about the fall is an absurdity. As to oxidation, there is no sign whatever of that, because the sequence of the accident was as I have said, the gradual extension of the internal pocket until it met the outside. The outside skin remained perfectly sound till the last moment, but the instant that the fault got through the skin you would get more than double the average stress on the sound metal, and then the whole thing would go off with a sound like a pistol shot and the roof fall down. I have no doubt that the circumference of the bar was hermetically sealed, not with pure iron, but with iron and slag. The absence of paint and so on would not affect the liability of the flaw to increase; rusting will not start a crack. Rusting of a welded bar starts, not an initial crack, but a ridge—just the reverse. It does not weaken the bar, but it causes a ridge to be visible where the weld is. There was no practical way by which this flaw could be detected in the roof. I anticipated considerable difficulty in finding it in Mr. Kirkaldy's laboratory. I told him to cut off the ends of the bars, to put them in a lathe and turn them, and to tell his men to watch carefully the shavings as they came off, because I have detected flaws, which were practically invisible, in that way. I told him to instruct his men if they saw a shaving break off at a particular part of the bar to make a chalk mark, and when the bar came round again to see if the shaving broke at the same place. If it should do so repeatedly, and you treat it with acid, you can then find the initial flaw. It was perfectly hopeless to think of discovering the flaw while the bar was in the roof. It was exceedingly difficult to find it even in the laboratory. I do not know of any other failures of bars of this description in a roof, but I know of any number of failures the same as this in other works, such as draw-bars of rolling stock. Having seen this failure, the general conclusion I come to with regard to tie-rods made up in this way is this—I should not trust a roof which was dependent upon a tie-bar of that size unless the walls were of such dimensions that, supposing one of the tie-bars broke, the adjoining principals and the wall combined would have sufficient strength to hold the whole thing up as an arch without a tie. In the present case, although the walls are weak, regarded as abutments to the arch, yet in conjunction with the two adjoining principals this thin wall held up the roof for about twenty minutes after the tie rod broke. That shows that if it had been a little bit stronger, it would have held the roof until there had been time to get wire ropes and make all safe. Therefore I should not condemn other roofs which are arches held by a single tie, if they complied with that other condition. I should like to see a roof painted every two or three years so far as appearance go, but to do so would not have affected such a flaw as this in the least. It is more an aesthetic than a practical matter. This roof had not deteriorated to any material extent from rusting. The actual deterioration of this bar from rusting amounted to one tenth of an inch on the mean diameter. After a roof had stood all the time that this had done, one would not suggest undertaking an examination for a fracture in a tie rod—at least you would not unless you were an impostor. If you were told to set out to examine it for that purpose you would say, "I am dealing with a fool and so I will deal with him according to his folly." There are no signs of deterioration in the quality of metal in the bar in question. I have never known of ironwork being materially damaged by loads not exceeding the elastic limit, no matter how many years they have had to endure them. With all the defects of the design, you could make this roof safe for a few hundreds of pounds. That could be done by the use of wire hawsers between the principals, and by strengthening a little some of the other connections, but I strongly advised the Board of Directors to face the question at once of replacing the roof in their own interests, and in that of the public, who would be always suspicious of the roof after this accident. I advised the Board of Directors to put up a low roof so designed that the station could be widened without any interference. They have decided to do that, and the design is now practically finished. I have seen the stress diagrams handed in by the Company's engineer, and have gone into them, and I confirm Mr. Tempest's calculations.

Conclusion.

The evidence in this case is, I think, conclusive on the cause of the accident, and there are no material points of conflict to deal with.

In December, 1902, a special examination of the roofs of Charing Cross and Cannon Street Stations was made to determine the necessity for any repair work. The result of this examination (evidence of Messrs. Tempest and Ellson) was to show that the general condition of the ironwork in the Charing Cross roof was good, and that no immediate repairs were required. The last occasion on which this roof had been painted and generally overhauled was in 1898. In June, 1905, after the cleaning and repair work of the Cannon Street roof had been completed, similar work was put in hand at Charing Cross.

In accordance with former practice, timber stages were slung under the entire surface of the south end bay of the roof. Each stage, in two portions, measured 35 feet in length, by from $12\frac{1}{2}$ to 20 feet in width. They were suspended by hanging irons from the roof purlins, and formed a series of platforms, at different levels, extending from wall to wall. Sail cloths were provided under the staging, which was close-boarded, as a protection for the workmen; and a temporary corrugated iron covering was erected over the platforms for the protection of passengers. A watchman was also appointed on the station platforms to communicate with the men on the staging. The work carried out consisted of cleaning and repainting all the ironwork, repairing the glass and zinc covering, and renewing certain of the sashbars, and lattice girders, which stiffen the roof purlins. It is clearly established that the ironwork in the principals and purlins was in no way interfered with or removed.

The greater part of the work on the south end bay of the roof had been completed, and about the middle of November the first movement of the staging northward was effected. At the time of the collapse, half the length of the staging extended on either side of the principal nearest to the wind screen, which was thus loaded with extra weight due to staging, men, necessary materials, etc. In addition, there appears to have been stacked outside on the crown of the roof zinc sheets and glass, which are estimated to have weighed about a ton.

After making all allowances for glass, &c., which had been removed, the total extra weight brought on the roof appears to have been about 32 tons, and it is calculated that of this total, the proportion carried directly by the first principal, which was the one to fail, was about $17\frac{1}{2}$ tons. This represents about 5 lbs per square foot of roof area supported by this principal.

On the 5th December, the repair gang of about 20 men were variously engaged in burning off paint, scraping and cleaning ironwork, repainting, &c., when about 3.33 p.m. a loud and unusual noise was heard in the roof. This time, I think, is best fixed by the evidence of Inspectors Stone and Lowes and Police Constable Fitt. The noise was audible enough to attract the attention, not only of the workmen on the roof, and of many persons in the station, but also of men engaged on the adjoining roof of the Avenue Theatre, and of others occupying rooms at the back of houses in Northumberland Avenue. It is variously described as resembling the sharp report of a gun, the dull crash of a locomotive striking buffer stops, the slower rending sound of iron rivets tearing apart, and the clash of a falling weight on iron sheeting.

People outside the station (Messrs. Maskell, Bacon, Lane, and Collings) describe how, after this unusual noise, they saw the outside surface of the station roof, about 30 to 40 feet from the south end (*i.e.*, over the first principal) suddenly sag or sink inwards, and then appear to remain in that condition. Workmen were observed to hurriedly climb off the stages on to the exterior of the roof, and then run away in different directions. Some of them shortly afterwards returned, and were occupied first on the staging, and then in removing material from the crown of the roof. Cracks were seen to form in the west wall of the station between its southern end and the third pilaster. The second pilaster, which carried the first principal, was seen to be leaning outwards, and bulging. The mortar crumbled at the joints, the wall overturned and fell outwards on to the roof of the Avenue Theatre. The end screen was dragged down afterwards and fell northwards, bringing down more of the west wall with it.

On the roof of the station some of the workmen on the stages appear to have recognised the first loud noise as proceeding from beneath them. They were alarmed by the stages suddenly sinking under them, and clambered out on to the roof to seek a safer position. Some of these men were met by their foreman Stirling, who had also heard the noise in his office, on the roof of the tank house at the south-east corner of the station. In answer to his question, they replied that something was wrong as the stages were sinking. They did not tell him that the tie rod had broken, though some of them from Foster's evidence must have seen this. Stirling called the men back, ran up the ladder on to the crown of the roof, and dropped through the ironwork on to the stage in the third panel from the west wall. This particular stage happened to be the easiest to get on to. He found that one of the diagonal braces in that panel was broken. The broken ends were then $1\frac{1}{2}$ inches apart. He shouted to the watchman on the station platform below him to stand clear of the staging. With the help of his men, the broken ends of the brace were lashed to the roof purlins, to prevent the possibility of their breaking away and falling. Stirling then set his men to work to lighten the weight on the roof, by removing the loose zinc sheets that had been stacked on the crown. Whilst engaged in this work the two end bays of the roof suddenly fell in. All this time neither he nor his men appear to have recognised that the roof was actually collapsing. No more unusual noises were heard, and the distortion of the roof, after the first sag took place, which caused the stages to sink, must have been proceeding very gradually.

Numerous witnesses stationed on the station platforms looked upwards when the first loud noise was heard, and describe that they saw one of the main tie rods under the staging on the western side was broken, and hanging downwards. The depression in the roof surface, noticed by persons outside the station, was visible from No. 6 platform (evidence of Inspector Stone), but not from Nos. 1 and 2 platforms immediately under the broken rod. None of these witnesses recognized the extent of the impending disaster. Steps were, however, taken to keep people away from Nos. 1 and 2 platforms, and action was taken by the watchman and others to stop trains from entering these platform roads. But down trains left Nos. 2 and 6 platforms at 3.35 and 3.39 p.m. respectively, and two up trains arrived at No. 6 platform at 3.34 and 3.39 p.m. About 3.45 p.m. a second loud rumbling noise was heard by these witnesses, followed by the fall of the two complete end bays of the roof. Signalman Bunn describes how he saw the wind screen fall over northwards, after the roof collapsed.

Owing to the great mass and weight of the falling débris, and to the necessity for safeguarding the remainder of the roof, it was not until mid-day on the 9th December that it was found possible (evidence of Inspector Chaplin) to trace the tie rodding of the fallen principal throughout its length. It was then found to be broken at one point only, viz., in the third panel from the west, about 13 inches from the third coupling joint.

The evidence proves beyond a doubt that the snapping of this particular tie-rod was the immediate cause of all that followed. The west wall, without the support of arched buttressing (as in the case of the east wall), yielded eventually to the severe thrust from the loosened bow of the first principal. But the time occupied—12 minutes—shows that not only did the wall offer great resistance to tearing apart, but that much work had to be accomplished in breaking away from the hold exercised on the crippled principal by the lines of purlins, which were stiffened by intermediate lattice girders, and in overcoming the resistance to distortion of the main rib itself.

Turning now to the broken tie-rod, the eastern end in falling buried itself like a bayonet two feet in the ground. This end was unearthed on the 7th December, but the fractured surface was already rusted and corroded, and told no tale. The western end fell on the timbering of No. 2 platform, and was covered with corrugated sheeting and fallen débris. It was thus fortunately preserved from the effects of damp and dirt. I saw it within a few minutes of the time it was uncovered on the 9th December. The surface of the fracture was then as clean and fresh as could be desired. The appearance was typical of a fracture at a badly formed weld. From the sketches (Plate II.) attached, it will be seen that approximately two thirds of the line of fracture is at an angle of about 56° with the axis of the bar, whilst the uppermost third is vertical. The surface of the fracture may be divided for the purposes of description into three parts (*vide* sketch). A belt A about an inch in width (along the vertical line of fracture) extends round the upper and northern half of the circumference of the bar ; over this area the fracture had the bright crystalline appearance of iron suddenly torn apart. In the centre of the bar can be seen a flaw or pocket B with a smooth fire-skin surface, surrounded by fragments of dark coloured ash ; this area is roughly circular in shape with a diameter of 1½ to 2 inches. The third portion C, mainly consisting of a belt 1½ to 2 inches in width round the lower and southern half of the circumference, was generally discoloured and corroded, with a spongy appearance common in ill-formed welds, but here and there small spots and pin-points, especially round the circumference, of clear crystalline appearance, showed signs of freshly fractured metal.

As set forth in the evidence given by Sir John Wolfe Barry, Sir Benjamin Baker, and Mr. Kirkaldy, there can be no doubt that the fracture occurred at a weld in the bar ; that the core of the bar B had never united, and had never possessed any value to resist tension ; that the surfaces of the area C had united, probably indifferently, except in the immediate neighbourhood of the circumference ; and that the flaw, which originated in central pocket B, had gradually extended outwards over the area C under the severe tensional stress to which (owing to the want of union in the centre) the bar had been so long subjected. The isolated bright spots and specks over the area C show that immediately before the bar snapped there was good metallic contact at these various points, as well as over the whole area A.

The total area of metal which was doing work, in resisting tension, at the moment when the bar broke may be roughly estimated at about one third of the whole area, or from 5 to 6 square inches. The total calculated stress (*see* table of stresses in Appendix), in tension was 81·5 tons, or from 13 to 16 tons per square inch of available metal. Taking into consideration the eccentric position of the bulk of the available area A, it will be admitted that so high a stress would be certain to cause rupture the moment the thread-like points of contact in the area C parted.

The normal stress in tension, due to weight of roof only, on this bar was about 61·5 tons. The additional stress brought to bear by weight of staging, &c., necessary for repair work, was thus 20 tons, or nearly 30 per cent. more. The bar was subjected to this greatly enhanced stress for three weeks continuously before it failed ; and prior to the middle of November had for four months been undergoing a stress 15 to 20 per cent. greater than would be due to weight of roof only. It is clear, therefore, I think, that the immediate cause of failure was the additional weight necessarily imposed on the principal in connection with the repair work, and it is reasonable to suppose that the failure would not have occurred at the moment it did, if the tie-bar had been subjected to stress from weight of roof only. It is equally clear that the weight of staging, &c., merely accelerated the failure, which, judging from the appearance of the fracture, was bound to occur at a comparatively early date. That the flaw was growing is plain from the fact that the bar successfully withstood equally high stress imposed for a long period in the year 1898, when staging of similar weight was used for repainting work.

Sir John Wolfe Barry and Sir Benjamin Baker state in their evidence that it is probable, judging from the procedure taken in the case of the New Street Station roof, Birmingham—the prototype of the Charing Cross Station roof—that the tie-bars were hydraulically tested before erection with a stress of 9 tons to the square inch (=144 tons on this particular bar), and that every examination and test of the ironwork was made, which the skill and care of engineers at that time could devise. Notwithstanding, the original bad flaw in the weld of this bar remained undetected.

Once the roof had been erected, the possibility of a serious flaw being in existence, and growing in size until it caused a failure has never before been recognized. This is the first known case of a tie-bar in a contained arch breaking under a reasonable stress. It would not, I think, have occurred to any engineer to make any special examination to discover the possible existence of such a flaw. Periodical examinations would be made to determine the extent of general repair work necessary. At such periods the visible weakening or loss of metal due to rust or corrosion could be gauged, the condition of the bolts and fastenings determined, and necessary action could be afterwards taken to clean and repaint ironwork, renew bars that were much decayed, and replace fastenings. But, as given in evidence, no practical method exists of detecting an interior flaw in a bar of this size under high tension, unless some sort of fissure in the outer surface was apparent. No apparent fissure could, I think, exist under such stress without the bar snapping immediately. The evidence of Mr. Kirkaldy, on the difficulty he experienced in his works of discovering and proving the existence of welds at both ends of these tie-bars, shows that the welding on the surface of the bars was very well executed.

I have not neglected to consider the possibility of other causes which might wholly or in part have occasioned the failure of the roof. I propose now to deal with the principal theories which have been suggested.

(*a.*) Reduction of strength by rust or corrosion, consequent upon want of maintenance. The tie-rod that broke had originally a diameter of 4½ inches, and a sectional area therefore of 15·9 square inches. Most of the paint which was laid on in 1898 had perished, and the surface of the bar was pitted considerably by rust. But from careful measurements (made by Mr. Kirkaldy) the mean diameter of the bar after fracture was found to be 4·4 inches (area =15·2 square inches), so that the actual loss of metal amounted to 4·4 per cent of the original area. This is an insignificant loss, and cannot be held accountable for the failure.

(*b.*) Fatigue of material, due to long continued stress, or vibration set up by the motion of trains, &c. There is no evidence to prove this, but rather the reverse. The test pieces cut out of the bar by Mr. Kirkaldy, close to the fracture, broke under a tensional stress of 20·6 tons per square inch, and showed a contraction of area equal to 40 per cent. The iron had the appearance and character of new metal.

(*c.*) Wind pressure. The afternoon of the 5th December was calm and still. The fact that, a fortnight previous to the failure, when the full weight of the staging was imposed on the principal, there was half a gale of wind blowing and that failure did not then result, goes to prove that the effect of the wind on a roof of this shape, sheltered by high walls, is very much smaller than has been generally estimated.

(*d.*) Disturbance of foundations, due to excavations in connection with the tubes of the Baker Street and Waterloo Railway. These tubes are nearest to the west wall of Charing Cross Station in Northumberland Avenue at the junction of Whitehall Place. The eastern tube is about 125 feet horizontally from the station wall. The extrados of this tube (11 feet 8½ inches in diameter) is 56 feet below the ground level, and 10 feet below the upper surface of the London clay. Any disturbance due to the excavation for these tubes would in the first place have affected the station viaduct, which carries the walls of the station. It would at once have shown itself in visible cracks in the arching of the viaduct. No such cracks have appeared since 1900, when the tubes at this point were constructed. No subsidence either has been experienced in the walls of the Avenue Theatre, which lies directly between the station and the tubes. There is, therefore, nothing to support this theory.

(*e.*) Absence of buttressing to the west wall of the station. The design of the roof, as has been stated in the description, was that of a contained arch. So long, therefore, as there was no failure in any integral part of the design, vertical pressure alone was brought to bear on the walls supporting the roof. That they were strong enough to stand this vertical pressure is, I think, proved by the fact that they carried the roof for so many years. Sir John Wolfe Barry states in his evidence that the buttressing to the east wall was decided upon after the roof had been erected, as a safeguard to the possible effect of wind pressure from south-westerly gales upon the western wall, which was at that time much more exposed than in the present day. From the point of design, at the time the roof was constructed, it cannot be said that buttressing was necessary, nor in fact would such buttressing have prevented this particular tie-bar from failing in the way it did.

I come to the conclusion, therefore, that the fall of the roof was brought about by the breaking of the tie-rod in the third panel from the west of the main principal nearest to the wind-screen. The fracture occurred at a weld, by reason of a flaw in the welding. This flaw, commencing in the heart of the bar, had gradually extended outwards. The additional weight of the temporary staging was the immediate cause of failure, but as the total stress in tension, at the time of failure, on the whole sectional area of the bar did not exceed 5·13 tons per square inch, I find that, for the necessary purposes of repair, such a stress was not in any way unreasonable, and could not be anticipated to cause danger of failure. Lastly, I do not consider that any reasonable precautions were neglected by the engineer or his staff in charge of the roof, or that it was possible by any practicable method to have discovered the flaw in the tie-bar.

The particular lessons to be learnt from this sad accident are as follows :--

1. That in old iron roofs of similar design, more especially where welded bars of any size have been used, there is danger to be guarded against of concealed flaws, which may grow in size under continued tensional stress, although in itself that stress may not be exceptional.

2. That unless additional security be afforded by the duplication or strengthening of the main tensional members there is possible risk of failure.

3. That where such risk of failure exists, it is necessary to consider whether the walls supporting the roof are in themselves sufficiently strong to resist the thrust which such failure will bring on them, and if not to strengthen them.

As regards Charing Cross, the Company have decided to remove the whole of the old station roof, and to replace it by one of the ridge and furrow type, on a lower level, with intermediate supports on the platforms. This work is proceeding, and in the meantime steps have been taken to relieve the tension on the tie-bars of all the remaining principals by taking up some of the strain with wire hawsers.

Before closing this report, I wish to draw attention to the work carried out by the engineering staff of the railway during the days immediately following the collapse of the roof. The falling ironwork struck and broke the tie-bar of the second panel from the east wall of the second main principal, and caused the tie-rodding to break away from the first and second coupling-joints. The three eastern panels of this truss were thus left unsupported by ties. The western wall was also forced out of the vertical by the thrust developed by this principal, which was left standing. The condition of affairs was highly dangerous, and a further collapse of the roof might have occurred at any moment. Wire hawsers were fixed to the feet of the second, third, and fourth principals, and the tension relieved by taking the strain with crabs. A raker was fixed against the west wall, and all the glass stripped off the roof between the second and third principals. Heavily strutted wooden towers were eventually erected to take the weight of the second principal. These works were carried out by night and day, under very considerable risk to life and limb, by the engineering staff of the railway. Their efforts, which had the happy result of rendering the remainder of the roof safe, call for special mention.

I have, &c.,

J. W. Pringle,

Major.

The Assistant Secretary,

Railway Department, Board of Trade.

APPENDIX.

Table of Calculated Stresses.

Members of Truss. (See lettering on Plate I.)	Roof Principal which failed.					Roof Principal tested at Contractor's works before erection (not that which failed).			Remarks.
	Total Sectional Area in sq. inches.	Stresses from weight of roof only, under normal conditions.		Stresses from weight of roof and staging at time of failure.		Total Sectional Area in sq. inches.	Stresses from distributed test load of 127 tons.		
		Total tons.	Per sq. inch, tons.	Total tons.	Per sq. inch, tons.		Total tons.	Per sq. inch, tons.	
Main Rib. A F ...	33·75	+ 77·5	+ 2·30	+ 101·5	+ 3·01	27·99	+ 156·0	+ 5·57	
B G ...	33·75	+ 71·5	+ 2·12	+ 95·0	+ 2·82	27·99	+ 145·5	+ 5·20	
C J ...	33·75	+ 69·0	+ 2·05	+ 93·0	+ 2·76	27·99	+ 142·0	+ 5·07	
D L ...	33·75	+ 67·5	+ 2·00	+ 92·0	+ 2·73	27·99	+ 141·0	+ 5·00	
E N ...	33·75	+ 66·5	+ 1·97	+ 91·0	+ 2·70	27·99	+ 139·0	+ 4·97	
Verticals. F G ...	6·75	− 8·7	− 1·30	− 11·0	− 1·63	6·75	− 17·0	− 2·52	
G J ...	6·75	− 4·2	− 0·62	− 5·3	− 0·79	6·75	− 7·5	− 1·11	
J L ...	6·75	− 4·2	− 0·62	− 5·3	− 0·79	6·75	− 7·5	− 1·11	
L O ...	6·75	− 5·7	− 0·85	− 7·5	− 1·11	6·75	− 11·0	− 1·63	
Diagonals. G H ...	3·00	− 6·1	− 2·05	− 9·0	− 3·00	3·00	− 15·0	− 5·00	
J K ...	3·00	− 5·2	− 1·73	− 7·2	− 2·40	3·00	− 13·0	− 4·33	
L M ...	3·00	− 3·0	− 1·00	− 4·5	− 1·50	3·00	− 8·0	− 2·66	
N O ...	3·00	—	—	—	—	3·00	—	—	
Tie bars. F P ...	19·63	− 60·5	− 3·07	− 79·0	− 4·02	17·72	− 121·0	− 6·83	
H Q ...	17·72	− 57·0	− 3·21	− 75·0	− 4·23	16·80	− 114·0	− 6·80	
K R*...	*15·90*	*− 61·5*	*− 3·87*	*− 81·5*	*− 5·13*	15·90	− 124·5	− 7·83	* Failure occurred in this bar. The area available to resist tension was about 6 sq. inches only (see Pl. II.).
M S ...	15·03	− 64·8	− 4·31	− 86·0	− 5·72	15·03	− 133·5	− 8·88	
O T ...	14·18	− 66·5	− 4·69	− 88·5	− 6·24	14·18	− 139·0	− 9·80	

Printed copies of the above Report were sent to the Company on the 13th June.