Assessment in fatigue of an orthotropic steel deck bridge under traffic loads and impact of abnormal loads. Case of Normandy bridge

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ASSESSMENT IN FATIGUE OF AN ORTHOTROPIC STEEL DECK BRIDGE UNDER TRAFFIC LOADS AND IMPACT OF ABNORMAL LOADS.
Case of the Normandy Bridge.

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ABSTRACT

Due to a request to open the Normandy bridge in France to abnormal loads, some detailed investigations have been carried out on the current traffic loads, and on the expected fatigue lifetimes, with and without the abnormal loads. This long span cable-stayed bridge is made of a steel orthotropic deck, quite sensitive to fatigue under traffic loads. Using the simplest standardized fatigue load model of the Eurocodes (LM3 of Eurocode 1991-2) is much too conservative and leads to unrealistic calculated lifetimes of a few years. Therefore, a real traffic load assessment was performed with a Weigh-in-Motion (WIM) system. A bridge WIM (B-WIM) system has been installed on the bridge, and the traffic loads were measured continuously over 7 months. The influence lines of the most sensitive details, mainly at the welds between deck plate and longitudinal stiffeners, at various transversal locations, were re-calculated with a 3-D finite element model (FEM), and compared to former measured influence lines. Fatigue lifetimes were assessed using the Miner's law, using successively a simplified load model made of a standard tridem axle, the measured traffic loads on the Normandy bridge, some measured traffic loads on other French motorways, and finally with a superimposition of the current traffic loads and the expected abnormal loads. The transverse location of the wheels on the deck has a great influence on the fatigue damage. With all these results, pratical recommendations were delivered to the bridge concessionary about the acceptability of the abnormal loads.

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Keywords: Fatigue, Fatigue Lifetime, Orthotropic Deck, Traffic Loads, Abnormal Loads, Load Effects, Stresses.

PROBLEM STATEMENT, METHODOLOGY AND CHALLENGE

There are only three bridges crossing the Seine river between the city of Rouen and Le Havre (located at the Seine's mouth), over 100 km. The suspended bridge of Tancarville, located 30 km upstream of Le Havre, with a total length of 1420 m and a main span length of 608 m, was opened in 1959. The suspension cables were replaced in 1996-99 because of the corrosion. The bridge of Brotonne, located 50 km upstream of Le Havre, is a cable-stayed bridge of 1278 m in length, with a main span of 320 m. It opened in 1977, but the truck traffic is now restricted because of heath problems. The bridge of Normandy is the latest built near to Le Havre, and opened in 1995. At that time, it was the longest span (856 m) cable-stayed bridge in the World, and its total length is 2141 m. Until now, none of these three bridges is open to abnormal loads, i.e. gross vehicle mass (GVM) exceeding the National (and European) legal limits, of 44 tons (40 tons in the European Union, EU). However, the port of Le Havre is the second busiest in France with 67 millions tons of freight and 2.6 million twenty-foot equivalent units (TEU) per year. Thus, a large number of heavy vehicles cross the Seine River to access to or to leave from the port, some of them carrying indivisible abnormal loads. Under the current regulation, these abnormal loads have to make a long detour of app. 200 km, through the city of Rouen, and to cross the city dowtown. Therefore, the prefet of Normandy asked to the Chamber of Commerce of the Seine Estuary (CCISE), concessionary of the bridge of Normandy, to investigate the feasibility and conditions of opening the bridge to abnormal loads (not divisible and exceeding the legal mass limits) up to 94-96 tons, 108 and 120 tons. The French Ministry of Transport, the conceding authority, supervises the study and the final decision of accepting or not accepting the abnormal loads. The concession contract ends in 2027, and by that time, the CCISE must return the bridge in a very good state to the French State.

The CCISE, acting as a responsible concessionary, first commissioned a consulting company (Quadric) to check the fatigue lifetime of the most sensitive and critical details, using the standardized fatigue load model (LM3) of the Eurocode EN1991-2 *(1)*. The LM3 consists of two tandem axles. The center to center distance of the LM3 tandem axles is 7.2 m.. Also each of the four axle loads weigh 120 kN. This model was found much too conservative for the bridge of Normandy, designed before the Eurocodes, and leads to unrealistic calculated lifetimes of a few years. Therefore, advised by Michel Virlogeux, the designer of the bridge (and of many other large bridges around the World), the CCISE commissioned in 2017 a study to the French Institute for Science and Technology of Transport, Planning and Networks (IFSTTAR). The proposed methodology was first to collect load data uder the current traffic on the bridge, because only the traffic volume (truck flow by category) was known using the bridge tolling information. However, the truck and axle loads remained unknown. These data were compared to three other traffic load patterns measured on other French motorways. The next step consisted to re-assess the influence lines of the most sensitive details by FEM calculations (done by Quadric), and to compare them to those measured in 1995 during the initial study in fatigue of the bridge *(2)*. Then a simplified fatigue assessment and lifetime calculation were carried out using a simplified load model made of a standard tridem axle of 27 tons, the maximum allowed mass on a tridem according to the European Directive 96/53/EC *(3)*. A more realistic assessment was done using the current traffic loads measured on the bridge of Normandy and the lifetimes were compared with those calculated with the three other traffic patterns, and with the results of the intial study of 1995 *(2)*. Finally the superimposition of the expected abnormal loads and the current traffic loads led to new fatigue lifetime assessment to evaluate the additional damage and lifetime reduction due to the abnormal loads.

The main question was to check if two daily crossings of four defined abnormal loads would significantly reduce the expected fatigue lifetime of the bridge.

NORMANDY BRIDGE STRUCTURE AND TRAFFIC LOAD ASSESSMENT

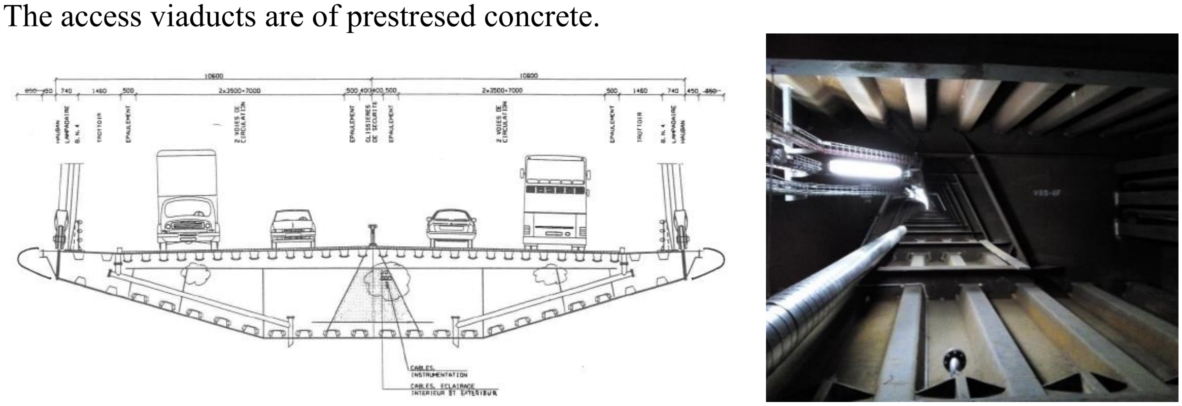
Bridge of Normandy: a long span cable-stayed bridge with an orthotropic deck

This exceptional bridge, built from 1989 until 1995, remained the longest cable-stayed bridge in the World until 2003, even if a longer cable-stayed main span was built in 1998 in Japan. The bridge crosses the Seine estuary between Le Havre and Honfleur, and carries the four traffic lanes of the motorway A29, plus two cycling paths and two footpaths (Figure 1). The main North-South traffic (Channel tunnel from UK, north of France and Benelux to Britanny and south west of France or Spain) crosses this bridge, as well as a significant part of the freight traffic to and from the port of Le Havre. However, the traffic Le Havre-Paris crosses the Seine River on the bridge of Tancarville (motorway A131).

(a) **(b)**

FIGURE 1 Bridge of Normandy, (a) arial view from the south, (b) view of the deck.

The two pylons of 215 m in height support a deck of 23.60 m in width with 184 cables, with lengths from 95 to 460 m. The main span of 856 m has a central part in steel of 624 m in length, and two parts of prestressed concrete (116 m from each pylon). The steel part is made of 32 segments of 19.65 m in length and 3.05 m in height, each being supported by two cables, one on each side. The steel deck is an orthotropic box with trapezoidal longitudinal stiffeners spaced by 0.60 m and of 0.30 m in height (Figure 2). The cross beams (diaphragms) are spaced by 3.93 m. The access viaducts are of prestresed concrete.



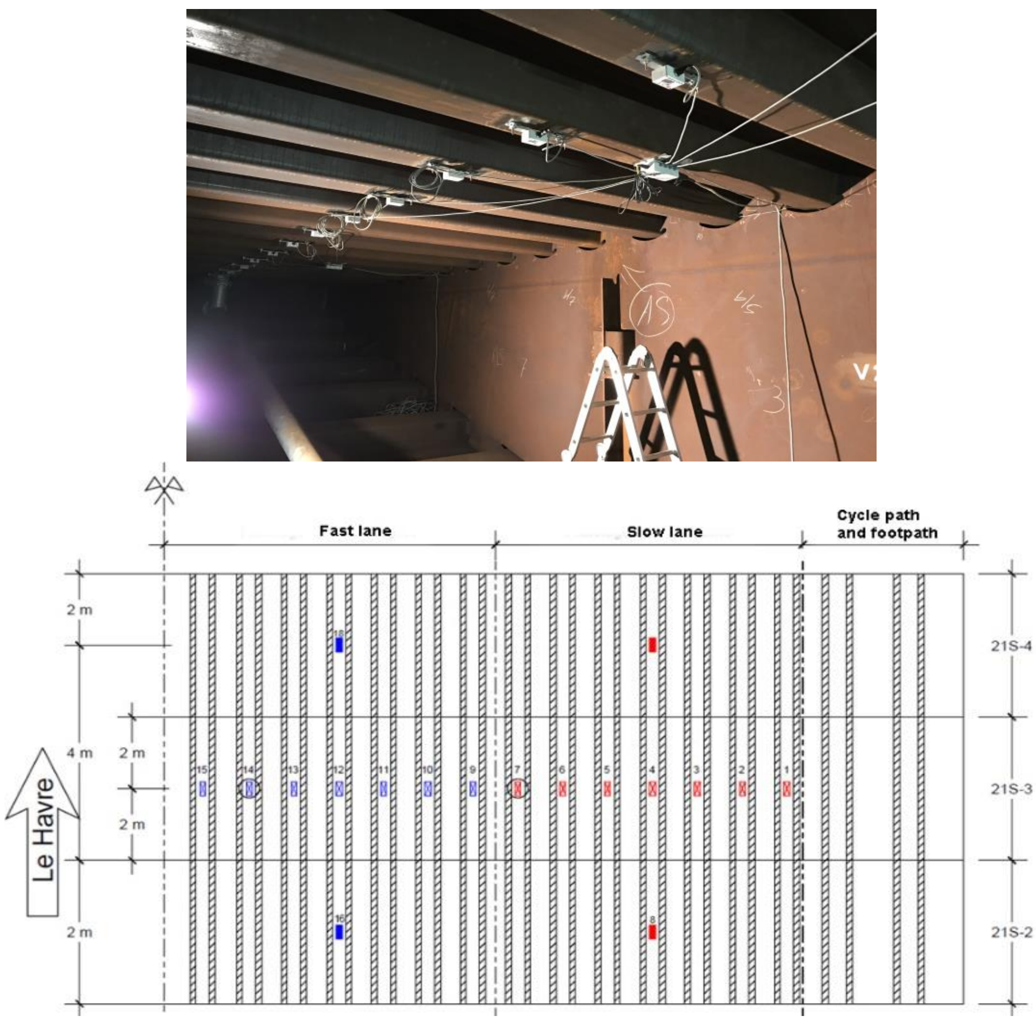
(a) **(b)**

FIGURE 2 Bridge of Normandy: (a) cross section of the steel orthotropic deck, (b) inside of the box.

The steel plate is 14 mm thick under most of the slow lanes and 12 mm thick under the fast lanes. The thickness of the stiffeners are respectively 7 and 6 mm. In the initial design, the thickness changed between the two traffic lanes, but a cycling path of 1.1 m in width was added afterwards, which shifted the left edge of the slow lane on the thiner part of the plate (Figure 8a).

Traffic load assessment using a bridge weigh-in-motion (B-WIM) system

Since the opening of the bridge of Normandy, the number of truck crossing the bridge every year raised from 200,000 to more than 1 million, for both directions. The tolling data give accurate statistics of the truck number per category (number of axles), but do not provide any information about their loading. Thus, the CCISE was highly interested to collect traffic loads using a WIM system. However, it is not easy to find an appropriate location to install a road sensor WIM system. On the steel deck, the pavement is too thin to install WIM sensors and the risk of water intrusion is too high to allow that. On the concrete deck, the longitudinal slope is above the limits proposed by the European Specification of WIM by COST323 *(4)*. In addition, close to the toll area the trucks are accelerating or breaking, which does not comply with the WIM requirements.



(a) **(b)**

FIGURE 3 (a) Extensometers of the SiWIM fixed under each longitudinal stiffener, (b) mapping of the instrumentation.

Therefore, it was decided to install a B-WIM system, which allows measuring axle and vehicle loads on an orthotropic bridge by instrumenting the bridge deck *(5, 6, 7)*. IFSTTAR and the Cerema (a French public technical organisation on risks, environement, mobility and planning) have installed in June 2017 the SiWIM commercialised by Cestel, a Slovenian company *(8)*. It has been installed in the south-north direction, in the 21st segment nearby the midspan, where the slope is neglictible. Both lanes in this direction have been instrumented (Figure 3), by:

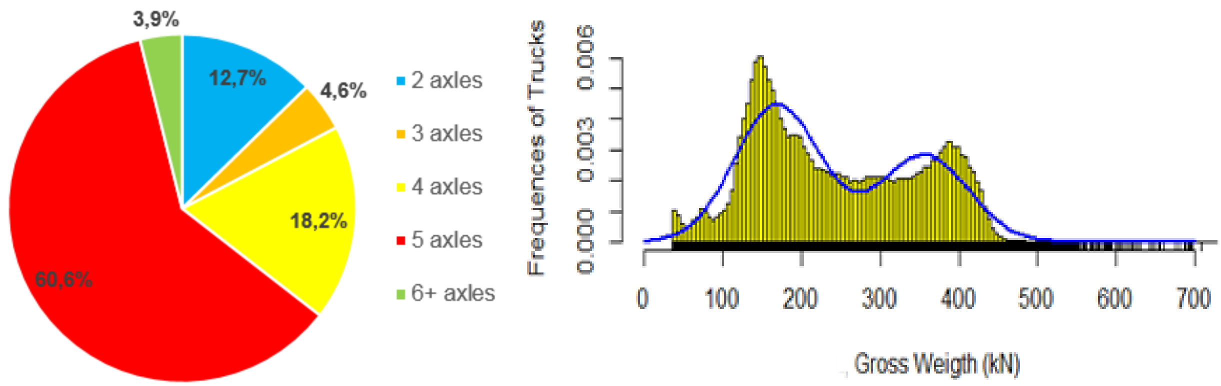
- 14 extensometers under all the longitudinal stiffeners (7 under the slow lane, and 7 under the fast lane), used for weighing (Figure 3b).
- 2+2 extensometers, one per lane in the two adjacent sections of the segment, across the cross beams, used to detect the coming vehicles and to measure its speed and axle spacing (Figure 3b).

The SiWIM has been configurated and calibrated jointly by a calibration truck whose weights and dimensions were measured in static. The accuracy was assessed according to the COST323 WIM specifications *(4)*, using 36 trucks (mainly 5-axle articulated T2S3) from the traffic flow, weighed in static on the toll area, over one day (August 2, 2017). The results (statistics of the relative errors, tolerances δ, confidence levels π and accuracy classes) are given in Table 1. The test conditions are R4/E1 (extended reproducibility/environmental repeatability) according to *(4)*. Four entities are in the accuracy class C(15), which is an average but acceptable accuracy. However the single axles are only in class D(25) because of a high scattering (standard deviation) due to load transfer between axles. This rather low accuracy does not affect too much the fatigue calculations because the mean bias are low, while a 10% increase of the scattering may induce an overestimation of the fatigue damage by app. 20%, and thus the lifetime is underestimated in the safe side.

TABLE 1 Accuracy of the SiWIM, August 2, 2017, in-service verification, R4/E1 *(4)*

Entity	Number	Mean (%)	Std Dev. (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	δ_c (%)	π (%)	Accepted class
Gross weight	36	-0.67	5.57	90.3	C(15)	15	11.5	11.5	97.5	D(25)
Groups of axles	41	-2.63	8.36	90.8	C(15)	18	17.7	14.7	95.2	
Single axles	68	-0.99	14.36	92.1	D(25)	30	29.2	24.2	93.0	
Axles in a group	148	-2.36	9.41	93.4	B(10)	20	19.5	9.7	94.1	

The system monitored and recorded the traffic (trucks above 3.5 tons) from July 2017 until May 2018, but for the fatigue assessment, the data until January 2018 were used. 237,584 trucks were recorded. The distribution of trucks per category (number of axles) and the gross vehice weight (GVW) probability distribution function (PDF) of all trucks are given in Figure 4 (a) and (b). The GVW PDF shows a bi-modal shape, as usually, and has been determined through expectation maximization algorithm. The first mode, centred at 166 kN, mainly contains 2- an 3-axle vehicles and unloaded or half-loaded 5-axle vehicles, while the second mode, centred at 350 kN, contains 4-, 5- and 6+ axle vehicles, fully loaded.



(a) (b)

FIGURE 4 Traffic on Normandy bridge (July 2017- January 2018): (a) Truck distribution by category, (b) Gross vehicle weight PDF.

The charateristics of this measured traffic are compared with those of three other traffic patterns, measured with WIM systems on the French mortorway network for further comparisons of their effects in fatigue (Table 2). This comparison gives an account of the sensitivity of the fatigue lifetimes to the traffic characteristics, and thus to cope for future traffic evolutions. The three other traffics were recorded on:

- The motorway A9 (south-east of France, to Spain) in Fabregues, south of Montpellier, in the northbound direction. It is one of the most trafficked motorway in France with the most aggressive traffic loads;
- The highway RN4 in eastern France (Paris-Nancy-Strasbourg), at Maulan in the westbound direction. It carries an average truck traffic with rather heavy loads;
- The motorway A20 (centre of France, Paris-Orléans-Limoges-Toulouse), at Massay, with a rather low truck traffic.

TABLE 2 Main characteristics of four French traffics (trucks) on highways and motorways

Site	Period	Days	Trucks Nb	ADTF	Prop. 2nd mode	Median 1st mode (kN)	Std. Dev. 1st mode (kN)	Median 2nd mode (kN)	Std. Dev. 2nd mode (kN)
Normandy bridge (A29)	17/07-18/01	183	224,435	1226	40 %	169	54	356	53
	18/01	29	35,710	1231	41 %	164	49	347	52
Fabrègues (A9)	15/01-06	189	901,231	4768	41%	234	85	371	27
Massay (A20)	2015	362	498,269	1376	20 %	241	79	384	27
Maulan (RN4)	2015	353	755,757	2141	29%	216	69	382	33

ADTF: Average Daily Truck Flow

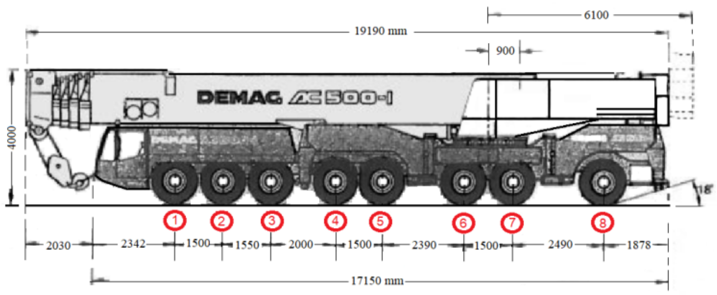
The traffic flow on Normandy bridge is quite low, comparable to the traffic on the A20 (Massay) which is a lower volume. However, it shows a rather large proportion of heavier trucks (the second mode of the GVW PDF contains 40% of the vehicles), but with a second mode 8% lower than on the other sites, but much more scattered (almost twice larger Std. Dev.).

Abnormal loads

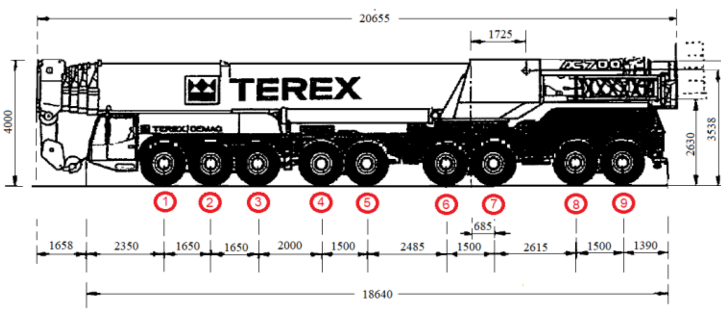
Four abnormal vehicles were considered as representatives of the potential very heavy loads, which could cross the bridge of Normandy if allowed:

- Two cranes of 96 and 108 tons, with 8 and 9 axles, all loaded at 12 tons (Figure 5);
- Two conventional abnormal 8-axle vehicles C1 (94 tons) and C2 (120 tons) (Figure 6).

Most of the wheels of these vehicles are equipped with extra wide tyres, e.g. 0.37 m in width. The vehicles C1 and C2 have a group of 5 close axles (1.55 m spacing) loaded at 12.8 and 17.5 tons, but each axle comprises 8 wheels (4 twin wheels).



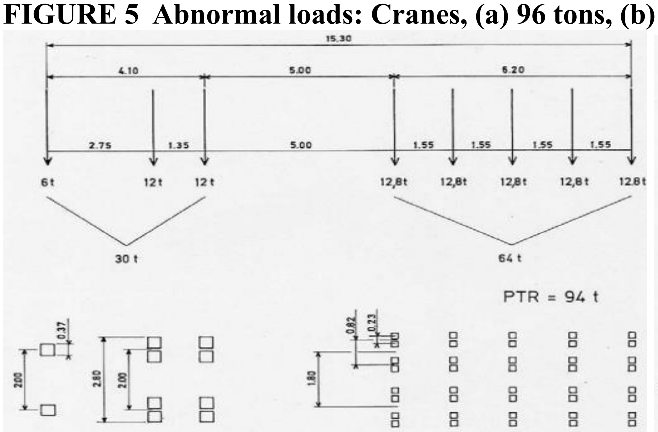
(a)



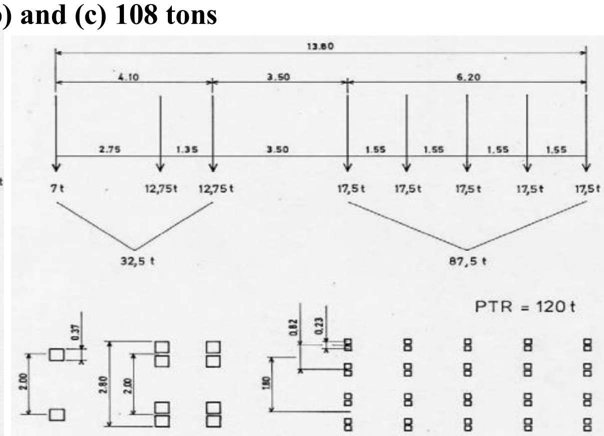
(b)

(c)

FIGURE 5 Abnormal loads: Cranes, (a) 96 tons, (b) and (c) 108 tons



(a)



(b)

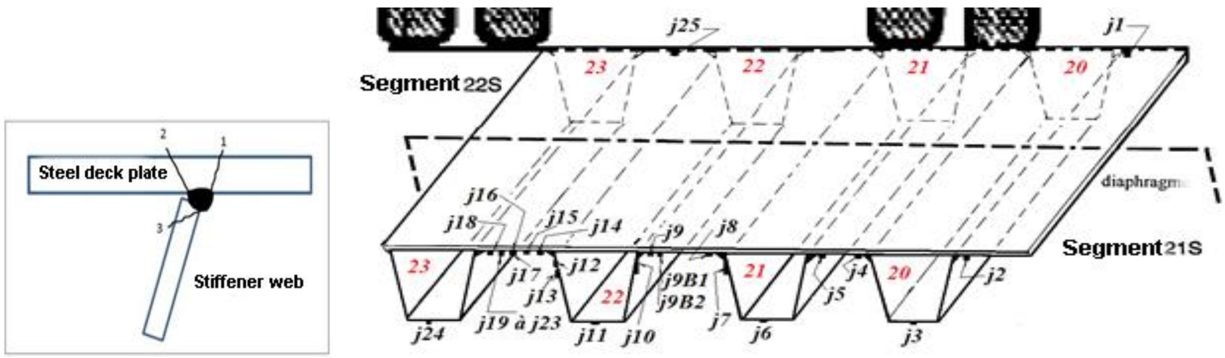
FIGURE 6 Abnormal loads and wheel layout: (a) C1 94 tons, (b) C2 120 tons

BRIDGE MODELING AND FATIGUE ASSESSMENT METHOD

Bridge modeling: influence lines

The most sensitive details in fatigue in an orthotropic deck under traffic loads are the welds between the upper deck plate and the lateral web of the longitudinal stiffeners, with a risk of crack propagation either in the deck plate or in the stiffener web (Figure 7a). These details are in the fatigue class 71 for a full weld penetration or in class 50 for a partial penetration, according to the

Eurocode 1993-1-9 *(9)*. For the study carried out in 1995 *(2)*, 35 strain gauges have been installed at the critical locations of two bridge sections (Figure 7b) to monitor the stresses induced by the traffic loads. The influence lines (IL) were measured using a 2-axle test truck, and more precisely its second axle is equipped with twin wheels and weigh 130 kN. This truck crossed the segment at various lateral locations and very slow speed and the IL were derived by an inverse calculation from the measured strains. They are shown in Figure 10a for three of the four most sensitive details, corresponding to the stress in three stiffener webs (gauges 7, 10 and 12). The last detail is in the deck plate (gauge 8), but the IL is not shown here.

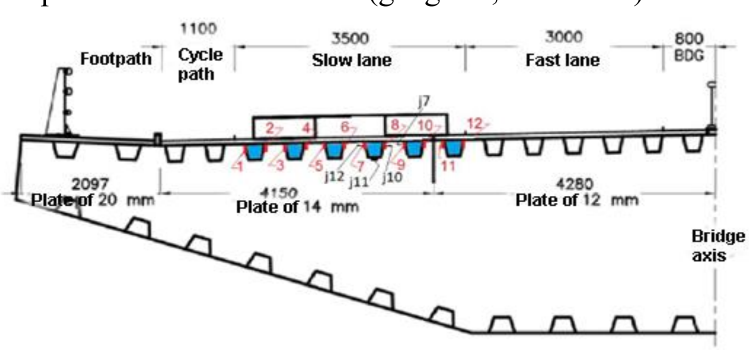


(a) **(b)**

FIGURE 7 Normandy bridge deck: (a) weld between the deck plate and a longitudinal stiffener web, and expected cracks under fatigue (named 1, 2 and 3), (b) Intrumentation of the deck with strain gauges (1995).

The stress range (ordinate of IL's peak) depend on the position of the wheels and the thickness of the deck plate. The gauges 7, 8, 10 and 12 are located under the deck plate of 14 mm in thick, but the gauges 7, 8 and 10 are closer to the thiner plate, which explains the stress range 50 to 60% higher than for the gauge 12. The IL of the gauge 8 is rather close to the IL of the gauge 7.

The IL of the sensitive details in the stiffener webs have been calculated by Quadric using a 3D-FEM in 2016 *(10).* The IL were provided at 12 locations (sections 1 to 12 in red, Figure 8a), for 6 lateral locations of the wheels (Figure 8b) as recommended by the EN1991-2 (Figure 9b), and the three types of wheel/axle configuration proposed by the Eurocode 1991-2: (A) single regular wheels, (B) twin wheels, and (C) single large tyre wheel (Figure 9). The calculated IL are given in Figure 10b for the most unfavourable transverse location (N°6) of a type B axle, and are compared to the measured IL (gauges 7, 10 and 12).

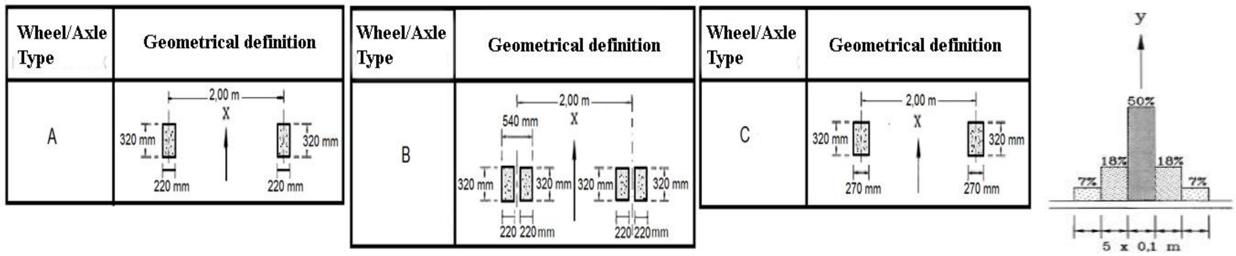


N°	Axle transverse location (slow lane)
1	Centred
2	Shifted by 0.10 m left
3	Shifted by 0.10 m right
4	Shifted by 0.20 m left
5	Shifted by 0.20 m right
6	Most unfavourable location

According to the EN1991-2 *(1)*

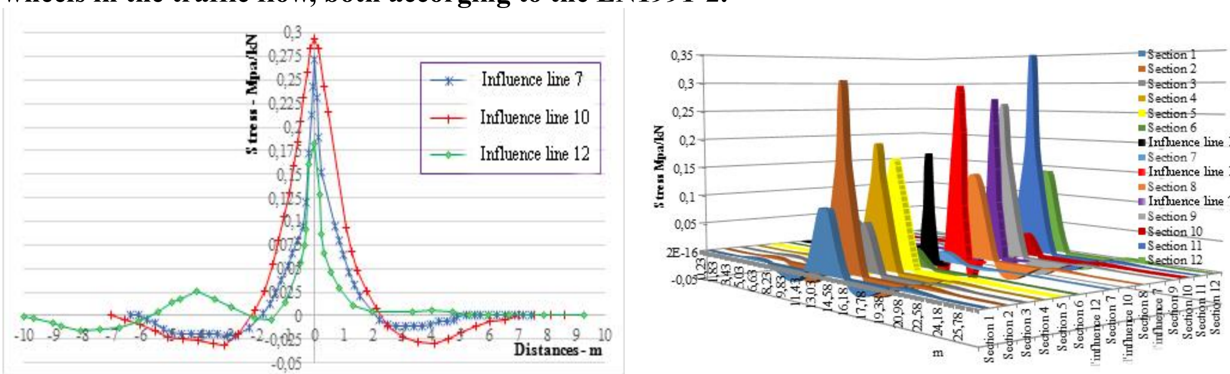
(a) **(b)**

FIGURE 8 (a) Sections (locations) of the calculated influence lines (1 to 12 in red), (b) Transverse locations of the (middle of) axle in the slow lane for the calculation of the influence lines.



(a) (b)

FIGURE 9 (a) Types of wheel/axle for load application, (b) statistical transversal distribution of the wheels in the traffic flow, both accorging to the EN1991-2.



(a) (b)

FIGURE 10 Influence lines of the critical details: (a) measured in 1995, (b) calculated by FEM in 2016.

According to the Figure 8a, the correspondance between the measured and calculated IL should be: gauge 7 = section 9, gauge 10 = section 8 and gauge 12 = section 7, and the wheel configuration is of type B. However, the geometry of the truck used in 1995 was slightly different from the modern truck one (Figure 9), with a slightly narrower wheel track. Moreover, the lateral location of the test truck in 1995 is not accurately known. Therefore, the measured and calculated influence lines do not exactly fit each to the other.

For the gauge 7 and section 9, the fit is excellent for the transverse location N°6 (Figure 10b). For the gauges 10 and section 8, the best fit is found for a transverse location between N°3 and 5, i.e. a right shift of 0.15 m. For the gauge 12 and section 7, the fit is found for the transverse location N°5, i.e. a right shift of 0.20 m.

This comparison allows performing the fatigue assessment using either the measured or the calculated influence lines. In the following, the measured influence lines were mainly used in order to compare the results to those gathered in 1995. However, if more detailed information could be get on the real transverse location of the wheels by more advanced WIM systems, the calculated influence lines would be more adapted.

Fatigue assessment method

The fatigue assessment is made according to the EN1993-1-9 *(9)*. The stress variations under traffic loads are accounted by the rain-flow method, and then the Miner's law is used to calculate the whole lifetime of the detail, using the relevant fatigue class and the corresponding S-N (fatigue) curve. The minimum required lifetime for the large bridge of Normandy is 120 years. However, the Miner's model has quite a lot of uncertainties, and the order of magnitude of the calculated lefetimes are more relevant than the accurate values.

In the following section, the fatigue assessment is made for several loading cases:

- A simple load model, less conservative than the LM3 of the EN1991-2, which consists of a tridem axle (3 x 9 tons or 88.3 kN = 27 tons or 265 kN, i.e. the maximum permitted load by the European Directive 96/53EC); the axle spacing is 1.3 m. We assume that this tridem crosses the bridge (in one direction, on the slow lane) 600 times per day, or has the same aggressivity in fatigue than two trucks. This assumption is validated in the next section;
- The real loads measured by the SiWIM on the bridge of Normandy (from July 2017 until January 2018), and the other traffic loads measured on other sites (Table 2);
- The abnormal loads (Figures 5 and 6) superimposed to the real traffic of the Normandy bridge.

The results are presented for the influence lines measured in 1995 by the gauges 7, 10 and 12. The calculated influence lines are used to assess the effect of the lateral scaterring of ht loads and to open some perspectives. The fatigue classes 71 (the most relevant one according to the bridge design and construction) and 50 (quite pessimistic, just in case of poor welds) are used.

RESULTS: STRESSES AND FATIGUE LIFETIMES

Stress calculation, ranges and variations

The main parameters of the S-N curves for the classes 50 and 71 are reminded:

- Class 71: fatigue limit (at 5 millions cycles) = 52.3 MPa, truncation limit (at 100 millions cycles) = 28.7 MPa;
- Class 50: fatigue limit (at 5 millions cycles) = 36.8 MPa, truncation limit (at 100 millions cycles) = 20.2 MPa.

According to the Miner's model, if the maximum stress range does not exceed the fatigue limit, the lifetime is infinite (no fatigue damage). Otherwise, the lifetime is finite, and all the stress cycles above the truncation limit are taken into account.

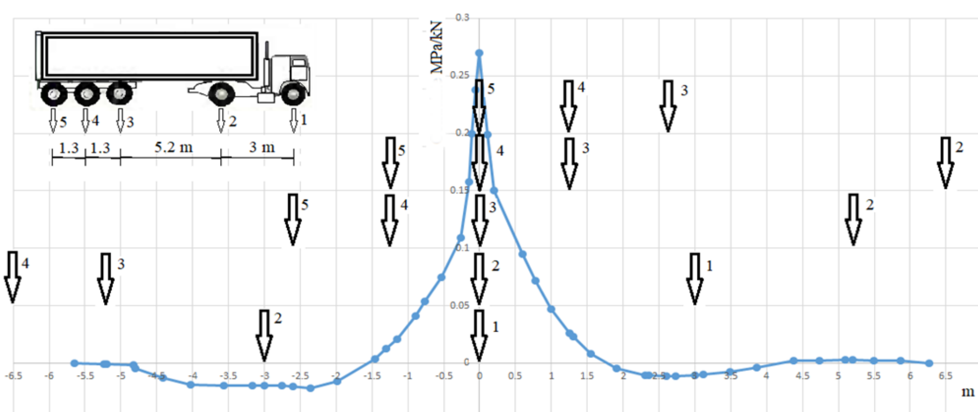


FIGURE 11 Assessment of the rain-flow histogram for a simple loading case: 5-axle articulated truck (axle loads 7, 12, 7-7-7 tons).

For the simple conventional load (the 265 kN tridem axle), as well as for any short series of axles or single truck, the rain-flow histogram is easy to assess manually. As shown in Figure 11 for a 5-axle articulated truck (T2S3), the first step consist to identify the longitudinal location of the load model (truck or group of axles) on the influence line, which provide a local extremum (maximum or minimum) of the stress path. In Figure 11, the arrows represent the axles with their rank, and each line or arrows corresponds to a local extremum of the stress path (the various axle loads are those measured by the SiWIM system, as explained above). After plotting these local extrema, it is easy to derive the rain-flow histogram, i.e. a few number of cycles and their amplitude.

First we assume that the influence lines are almost symmetrical, with a peak (maximum) value and two negative parts, as shown in Figures 10a and 11 (but for the gauge 12). Then while the tridem is crossing the influence line, according to the axle spacing (1.3 m) and the abscissa of the influence lines, two minima are reached when the centre of the tridem is close to the minima of the influence line, and one maximum when the tridem is centred on the peak of the influence line. Assuming that the two minima are close (which is the case), the rain-flow only contains one cycle with a range of σ_{max}-σ_{min}.

TABLE 3 Stress variations, rain-flow and ESAL for a tridem axle (3 x 88.33 kN = 265 kN)

	Max IL (MPa/kN)	Min IL (MPa/kN)	σ_{max} (MPa)	σ_{min} (MPa)	Cycle (MPa)	ESAL (kN)
IL 7	0.2720	-0.020	29.8	-1.7	31.5	108
IL 10	0.2942	-0.031	38.1	-2.7	40.8	126
IL 12	0.1823	-0.016	17.2	-1.4	18.6	94
IL 8	0.2702	-0.0199	27.3	-1.8	29.1	100

Table 3 gives the results for the tridem axle and the Equivalent Single Axle Load (ESAL) providing the same unique stress cycle (rain-flow), and thus the same elementary fatigue damage.

For a whole traffic record, a computer program is performing the same procedure for all the series of vehicles crossing the bridge. The local extrema are identified and stored, and then the rain-flow histogram is computed, for each influence line and traffic path. IFSTTAR uses the CASTOR/POLLUX software, which calculated the convolution of the influence lines and the measured axle loads. Therefore the input are the WIM data recorded on site, and the influence lines. The output are the rain-flow histograms and the lifetimes, depending on the fatigue class.

TABLE 4 Stress variations and rain-flow cycles for the four abnormal loads

		Cycles (MPa)		Cycles (MPa)		
		Crane 96 t	Crane 108 t		C1	C2
IL 7	Tridem	36.5	34.9	single axle	16.0	18.7
	Tandem	2 x 34.8	3 x 34.8	tandem	36.6	38.9
	single axle	32.0	-	5-axle group	39.1	53.5
IL 10	Tridem	45.3	42.4	single axle	17.3	20.2
	Tandem	2 x 40.2	3 x 40.2	tandem	42.7	45.4
	single axle	34.6	-	5-axle group	48.2	66.0
IL 12	Tridem	22.9	21.9	single axle	10.7	12.5
	Tandem	2 x 22.5	3 x 22.5	tandem	23.1	24.5
	single axle	21.5	-	5-axle group	24.5	33.6
IL 8	Tridem	33.0	32.3	single axle	15.9	18.6
	Tandem	2 x 32.8	3 x 32.8	tandem	34.7	36.9
	single axle	31.8	-	5-axle group	35.7	48.7

As explained in Figure 11, the stress cycles induced by the four abnormal trucks described in Figure 5 and 6 are simply computed by axle group, because the low spacing between axles and the spacing between groups of axles longer than the influence lines (positive part). Table 4 gives the four stress cycles induced while the cranes are crossing the influence line, and the three cycles induced by the C1 and C2 vehicles. Some of these cycles have an amplitude below the truncation limit, and therefore do not contribute to the fatigue damage. This is the case for the front axle of the vehicles C1 and C2. For these vehicles, the 5-axle group induces only one stress cycle, as the tridem because of the short spacing of the axles.

Fatigue lifetime assessment

Table 5 give the computed lifetimes for the four traffic paths (Normandy/A29, Fabregue/A9, Massay/A20 and Maulan/RN4), compared to the lifetimes resulting of the 600 daily crossings of the tridem, for both fatigue classes (50 and 71). The results are consistent. The traffics of A20 and RN4 gives lifetimes of the same order of magnitude than the traffic of A29 (bridge of Normandy), event if the RN4 traffic is a bit more aggressive. The traffic of A9 is much more aggressive, one of the most aggressive in France, but it will never occur on the bridge of Normandy. The lifetimes are also consistent with those calculated in 1995. The lifetimes for the IL10 even in class 71 are a bit short, and the calculation seems to be pessimistic.

TABLE 5 Lifetimes (in years) of the four main details under the tridem and the four traffics

	Class 50					Class 71				
	Tridem	A29	A20	RN4	A9	Tridem	A29	A20	RN4	A9
IL 7	61	32	29	24	7	352	254	296	274	75
IL 10	20	11	7	6	2	96	57	40	33	10
IL 12	∞	691	237	131	43	∞	61279	35145	13445	4426
IL 8	92	62	46	45	10	528	586	588	573	113

The effect of the abnormal vehicles is assessed by calculating the damage induced by two crossings per day (but Sundays and public holydays) of each of the four vehicles. This frequency was given by the CCISE as the basic assumption and leads to 300 crossing per year. The stress cycles of Table 4 allow the calculation of the elementary damage for each crossing of one abnormal vehicle, and then multiplying it by 300 gives the annual damage due to each abnormal vehicle i: D_i. The lifetime L_i of the detail submitted only to the abnormal vehicle i crossings is:

$$L_i = 1/D_i \quad (1)$$

The lifetimes for each abnormal vehicle and the three most sensitive details are given (in years) in the first lines of each part of Table 6 (by detail), for the fatigue classes 50 and 71. The lines below give the percentage r_i of lifetime reduction due to the abnormal vehicle i, derived from the lifetime L of the detail under the current traffic of the A29 (Table 5):

$$L'_i = 1 / (1/L + 1/L_i) \quad (2)$$

is the lifetime under the superimposition of the current traffic and the abnormal vehicle i, calculated as the harmonic mean of L and L_i, and then:

$$r_i = (L- L'_i)/L \quad (3)$$

The two last columns on the right of Table 6 gives the lifetime L_a of the detail under the superimposition of the four abnormal vehicles, i.e. the harmonic mean of the L_i, $1 \leq i \leq 4$, and below the percentage of lifetime reduction due to the four abnormal vehicles, computed with the formula (3), replacing L'_i by L_a.

TABLE 6 Contribution of the abnormal loads to the fatigue

Veh.	Crane 96 t		Crane 108 t		C1 (94 t)		C2 (120 t)		Total	
Class	50	71	50	71	50	71	50	71	50	71
LI 7	2823	16296	2751	15883	4158	22923	2088	6873	696	3190
	1.12%	1.53%	1.15%	1.57%	0.76%	1.10%	1.51%	3.56%	4.40%	7.37%
LI 10	1606	7248	1540	7247	2323	8923	1161	3567	390	1496
	0.68%	0.78%	0.71%	0.78%	0.47%	0.63%	0.94%	1.57%	2.74%	3.67%
LI 8	3821	22063	3793	21900	5766	33293	2689	10467	934	4618
	1.60%	2.59%	1.61%	2.61%	1.06%	1.73%	2.25%	5.3%	6.22%	11.26%

The two cranes induce very close individual damage in fatigue, which is not surprising because they have the same axle loads and induce very similar stress cycles. The vehicle C1 is less aggressive than the cranes but the C2 is much more because of the 17.5 tons axles. Finally, the lifetimes of the details could be reduced by 3 to 11% if the abnormal loads are allowed and as frequent as assumed. However, the damages assessed for the four abnormal vehicles are rather overestimated, because of the very wide tyres of 0.37 m in width instead of 0.22 or 0.27 m as assumed by the EN1991-2, and for the influence lines assessment. However, the overestimation is even higher for the vehicles C1 and C2, because of the 8 wheels under five of their eight axles. The sharing of the axle loads on more wheel and surface, all along the axle width, and thus on more longitudinal stiffeners, highly reduces the stresses in the details.

In addition, the fatigue assessment made at this stage neglects the lateral random distribution of the wheel path. If applying the statistical distribution proposed by the EN1991-2 (Figure 9b) for the whole traffic loads, the lifetimes could be significantly increased. Some preliminary calculations indicates that these lifetimes could increase by 50 to 100%.

CONCLUSIONS

IFSTTAR provided its expertise to install and operate a B-WIM system (the SiWIM) on the orthotropic deck of the bridge of Normandie, to measure the traffic loads over almost 11 months, and used 7 months of data to assess the lifetimes of the most sensitive details in fatigue. The influence lines measured in 1995 were double-checked by comparison with 3D-FEM calculations done by a consulting company Quadric, which was involved in the bridge design.

The effects of single vehicles or even of a tridem axle were simply calculated, which allowed assessing the potential contribution of the proposed abnormal vehicles to the fatigue damage, and thus the risk of lifetime shortening. It was shown that the lifetimes would not be shortened by more than 5 to 10%, even using rather conservative assumptions and neglecting the posiive effects of very wide tyres and 8-wheel axles on the abnormal vehicles. The methodology used may be applied to all orthotropic deck bridges, and even some other types of steel bridges. The study could benefit of further analysis, using more detailed computed influence lines or surfaces, and taling into account the geometry of abnormal vehicles and the lateral scattering of the wheel paths.

Finally, this study could be refined by using the real wheel imprints for each type of tyre mounted, and above all for the cranes and abnormal loads. Because these abnormal vehicles are equipped with wider tyres than the test truck used in 1995 to assess the influence lines, the stress amplitudes would be reduced for the same loads. And the fatigue lifetime would be extended. The results provided here are thus a bit conservative.

Author Contribution Statement

The authors confirm contribution to the paper as follows: study conception and design: B. Jacob, F. Schmidt; data collection: M. Arroyo, F. Schmidt; analysis and interpretation of results: M. Arroyo, B. Jacob; draft manuscript preparation: B. Jacob, F. Schmidt. All authors reviewed the results and approved the final version of the manuscript.

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