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Advanced procedures for design of bolted connections

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Abstract. Design of bolted slip resistant connection are integral part of design of steel bridges. In recent years, Component Based Finite Element Method (CBFEM) has been increasingly expanding in modelling of structural joints. The proper models of bolts play the major role in prediction of connection stiffness, resistance and deformation capacity. This contribution will describe the influence of pull and shear interaction for correct design of a group of bolts. The second part will be focussed to an advanced model of slip resistance bolts. The last chapter presents the advantages of procedure on examples of various bridge connection, which design was supported by CBFEM.

1. Introduction

Curve fitting procedures based on experimental evidence were and are still used for safe and economical design of connections. Based on analytical models of resistance of connectors, as welds, bolds, and plates, and the estimated lever arm of internal forces was and still is predicted resistance of connection. Zoetemeijer [1] was the first who equipped this model with estimation of stiffness and deformation capacity. The elastic stiffness was improved in the work of Steenhius, see [2]. Basic description of components behaviour in major structural steel connections was prepared by Jaspart for beam to column connections [3] and by Wald et al for column bases [4]. Method implemented in the current European structural standard for the steel and composite connections, see [5] and [6], is applied in majority of software for structural steel used in Europe. The idea was generalised by da Silva [7] for 3D behaviour including nonlinear parts of behaviour. Procedure starts with decomposition of a joint to components followed by their description in terms of normal/shear force deformation behaviour. After that, components are grouped to examine joint moment-rotational behaviour and classification / representation in a spring/shear model and application in global analyses. Advantage of this often called Component Method (CM) is integration of current experimental and analytical knowledge of connections components behaviour, bolts, welds and plates. This provides very accurate prediction of behaviour in elastic and ultimate level of loading. Verification of the model is possible using simplified calculation. Disadvantage of CM is that experimental evaluation of internal forces distribution is available only for limited number of the open section joint configurations. In temporary scientific papers, description of atypical components is either not present or has low validity and description of background materials. The CM´s is not developed for hand calculation but as a method for preparation of design tables or software tools. Models of hollow section connections are described in Ch. 7 of

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EN1993-1-8:2006 [5] by curve fitting procedures based on mechanical and numerical experiments. Their component representation is prepared according to the curve fitting procedures available based on selection of the suitable level arms and effective widths.

The global analyses of steel structures is today carried out FEA and all the traditional procedures are not used any more (like force method, three moment equation, Cremon´s pattern, the Cross method or the method distribution moments). In current fast development of software ability connections ready to be designed by FEA and thousands experiments is available the validation process. This paper describes the model of bolts available for Component Based Finite Element Model (CBFEM) which is a multilevel FEA method to design connections of steel structures [8] and its application to steel riveted bridges. The steel plates in connection are analysed in FEA by shell elements as separate plates connected by restrains. The proper behaviour of connectors, of bolts, welds etc., is treated by introducing components representing well its behaviour in term of initial stiffness, ultimate resistance and deformation capacity.

2. Bolted connections

In CBFEM are components as bolt and rivet modelled by a dependent nonlinear springs. The deformation stiffness of the shell element, which models the plates, distributes the forces between the bolts and simulates the adequate bearing of the plate.

2.1. Bolt in tension

The spring of a bolt/rivet in tension is described by its initial deformation stiffness, design resistance, initialisation of yielding and deformation capacity. The initial stiffness is derived analytically as

$$k = \frac{EA_s}{L_b} \tag{1}$$

where E is the Young's modulus, A_s the tensile stress area of a bolt and L_b the bolt elongation length.

The model corresponds well to experimental data, see [9]. For the initialisation of yielding and the deformation capacity is assumed that the plastic deformation occurs in the threaded part of the bolt shank only. The load-deformation diagram of the bolt is shown in Figure 1 and is derived for

$$F_{t,el} = \frac{F_{t,Rd}}{c_1 \cdot c_2 - c_1 + 1} \tag{2}$$

$$k_t = c_1 \cdot k;\ c_1 = \frac{R_m - R_e}{\frac{1}{4} \cdot AE - R_e} \tag{3}$$

$$u_{el} = \frac{F_{t,el}}{k};\ u_{t,Rd} = c_2 \cdot u_{el};\ c_2 = \frac{A \cdot E}{4 \cdot R_e} \tag{4}$$

where k is the linear stiffness of bolt, k_t the stiffness of bolt at the plastic branch, $F_{t,el}$ the limit force for linear behaviour, A the percentage elongation after a fracture of bolt, $F_{t,Rd}$ the limit bolt resistance and $u_{t,Rd}$ the limit deformation of bolt. The design values according to ISO 898:2009 [10] are summarised in Table 1.

Table 1. Bolt parameters in tension, based on ISO 898:2009 [10].

Grade	R_m [MPa]	$R_e = R_{p02}$ [MPa]	A [%]	E [MPa]	c_1 [-]	c_2 [-]
4.8	420	340	14	2,1E+05	0,011	21,6
5.6	500	300	20	2,1E+05	0,020	35,0
6.8	600	480	8	2,1E+05	0,032	8,8
8.8	830	660	12	2,1E+05	0,030	9,5
10.9	1040	940	9	2,1E+05	0,026	5,0

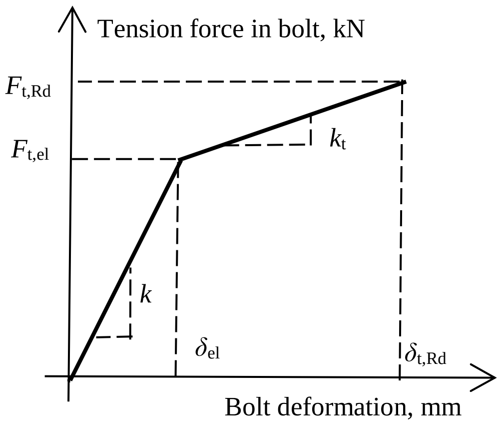

Figure 1. Load–deformation diagram of the bolt in tension .

2.2. *Bolt in shear*

The initial stiffness and the design resistance of a bolt in shear is in CBFEM modelled according to cl. 3.6 and 6.3.2 in EN1993-1-8:2006. The spring representing the bolt in shear has bi-linear force deformation behaviour. Deformation capacity is considered according to [8] as

$$\delta_{pl} = 3\ \delta_{el} \tag{5}$$

Initialization of yielding is expected, see Figure 2, at

$$F_{\mathrm{v,el}} = 2/3\ F_{\mathrm{v,Rd}} \tag{6}$$

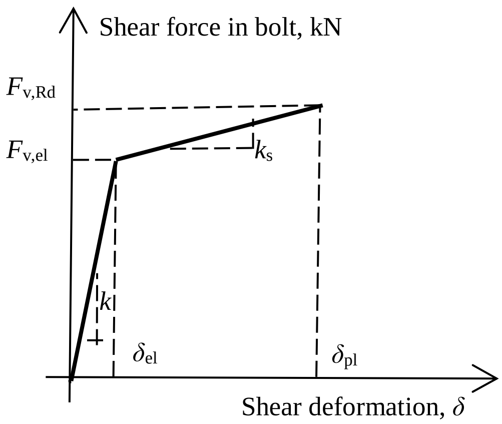

Figure 2. Force deformation diagram of the bolt in shear.

2.3. *Bolt interaction*

A combination of a shear and a tension in a bolt is expressed in EN 1993-1-8:2006 in Tab. 3.4 by a bilinear relation and checked as

$$\max\left\{\frac{F_{t,Ed}}{F_{t,Rd}}, \frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1{,}4\ F_{t,Rd}}\right\} \leq 1{,}0 \tag{7}$$

where $F_{v,Ed}$ is the acting bolt shear force, $F_{t,\ Ed}$ is the acting bolt tensile force, $F_{v.Rd}$ is the bolt shear resistance, $F_{t.Rd}$ is the bolt tensile resistance. A condition limiting the bolt resistance is showed in Figure 3.

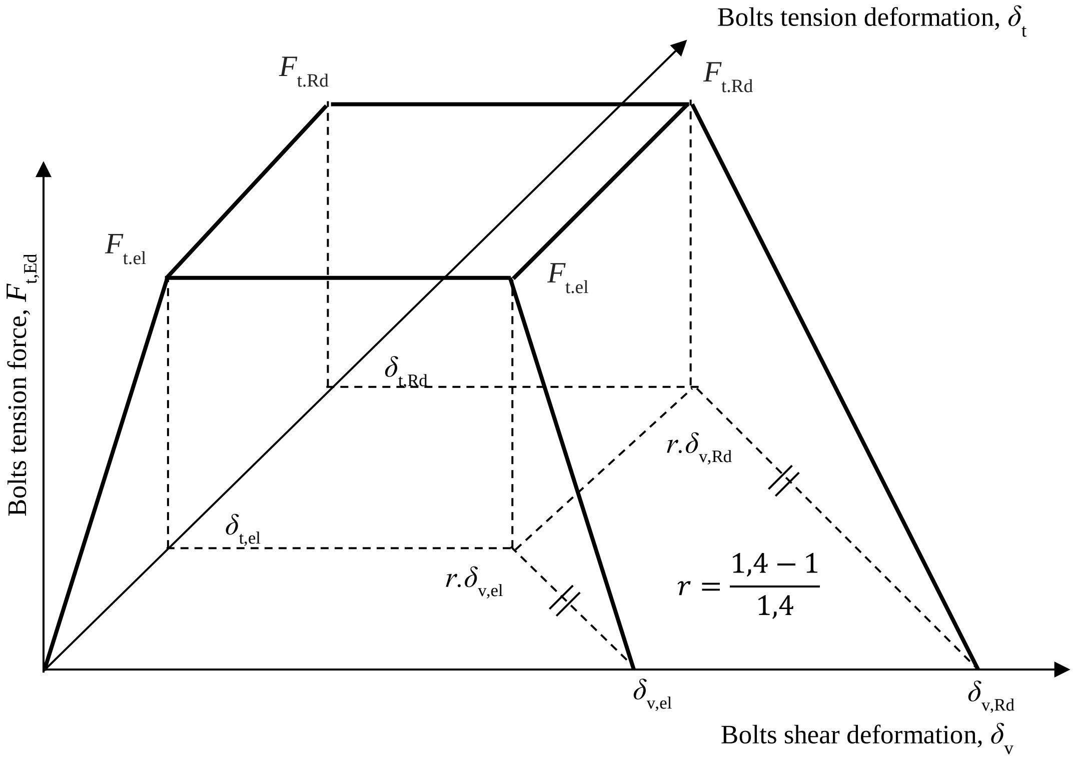

Figure 3. Bolt tension force as function of deformation in shear and tension.

2.4. *Preloaded bolts*

In connection with preloaded bolts is transferred the shear force by friction between both surfaces. Compare to regular bolts is in controlled the friction and the preloaded force. The final resistance is assured by bolt shearing and bolt and plate bearing after the slippage of bolt in the hole. In EN 1993-1-8:2006 is summarized the resistance of preloaded bolts classes 8.8 and 10.9 in Ch. 3.9. The bolts are expected to be preloaded to 70% of its strength f_{ub}. It is expected that the bolt deforms 80 % and the plates 20 %. If the external tensile force $F_{t.Ed}$ to joint in direction of the bolt is applied, the slip resistance will be reduced

$$F_{s,Rd} = k_s\, \mu \frac{0{,}7 f_{ub} A_S - 0{,}8 F_{t,Ed}}{\gamma_{M3}} \tag{8}$$

where k_s is the bolt hole size factor, μ the slip factor, f_{ub} is the bolt strength and A_s is the bolt area in tension.

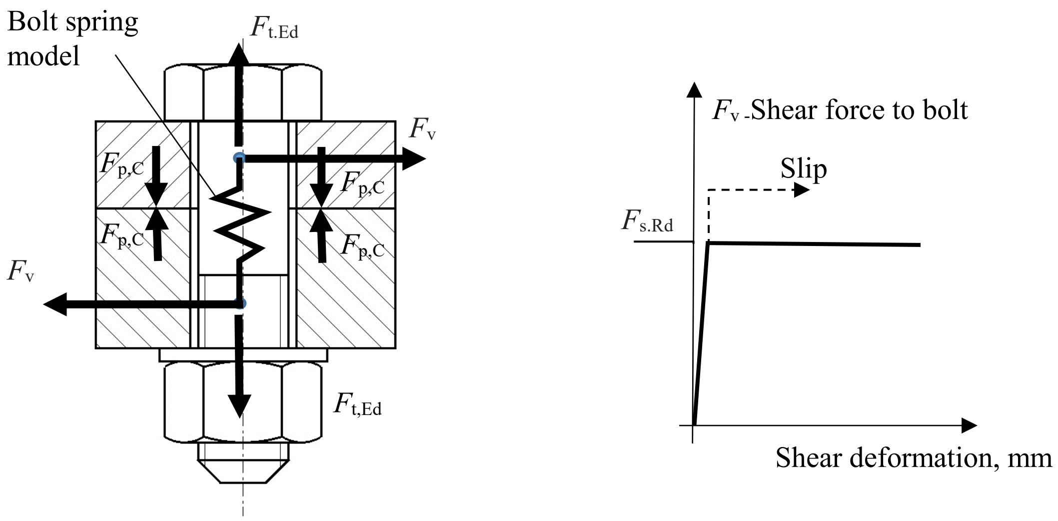

Figure 4. Shear characteristic of the preloaded bolt.

In design numerical model the component preload bolt is simulated either as nonlinear spring using the preloading force and deformation or by restrains between surfaces, which are representing the friction, with a spring, which is including a preloaded force in the bolt. For the bolt component represented by the preloading force and its slip deformation is the model similar to a conventional bolt model. The shear characteristic is shown in Figure 4. The initial linear shear stiffness is determined from the stiffness of the cylinder under the head of the bolt and it is practically rigid. The shear force limit includes the external tensile load to the bolt in accordance with EN 1993-1-8:2006. The advantage of this simplified model is its computational stability and low demands of the FE model and the consistence of results with cl. 3.6.2.2. The model does not respect the actual distribution of contact pressures between the plates and the history of preloading, but models the bolted connection including the bolt and plates deformation well, see Figure 5.

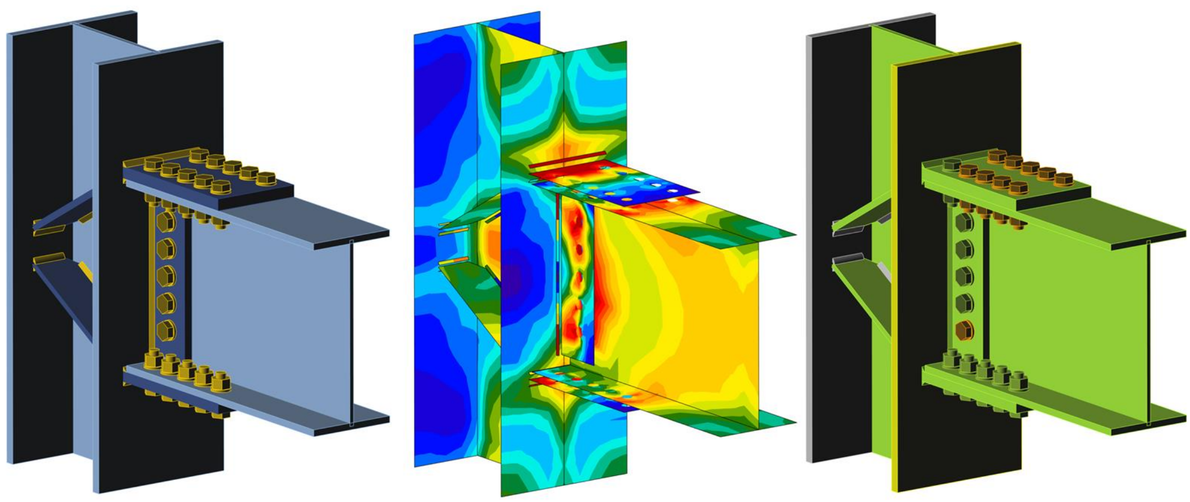

Figure 5. Bolted slip resistant connection,
configuration, von Mises stresses and strains at design stage

3. Application for assessment of old steel bridges

The industrial development in the beginning of the last century would not be successful without the transport infrastructure. At those days, many steel riveted bridges were built in the Czech Republic and also all over the world. Those bridges are usually at the end of their service life, however, the lack of the financial sources forces the infrastructure owners for operating them much longer. To do that, the extensive structural assessment of those bridges have to be organised, in order to evaluate the load capacity according to the existing state, corrosion weakening and possible fatigue damages. As majority of those have used riveting for the connections, the behaviour of the joints is very important for the bridge numerical model.

Traditionally, truss bridges were analysed under certain assumptions, such as the members are loaded only by axial forces. This assumption is only true if the connections allow the rotation between elements, which in reality is not the case. There are always certain moments transmitted depending on the stiffness of the connection. Unfortunately, the riveted joints are mostly complicated and hard to analyse by standard FEM software. However, CBFEM models those joints and obtains the initial stiffness, which is an essential input to the global numerical model.

In last two years, several bridges were analysed with the help of the CBFEM method and software tool [11]. The results of the impact of the connection stiffness on the behaviour of a historical steel railway bridge are shown here together with the main results [12]. The Figure 6 shows the old steel heritage bridge in Prague, Vyšehrad, where a number of models were created, such as the connection between top chord and bearing vertical, show on the Figure 7 from [13].

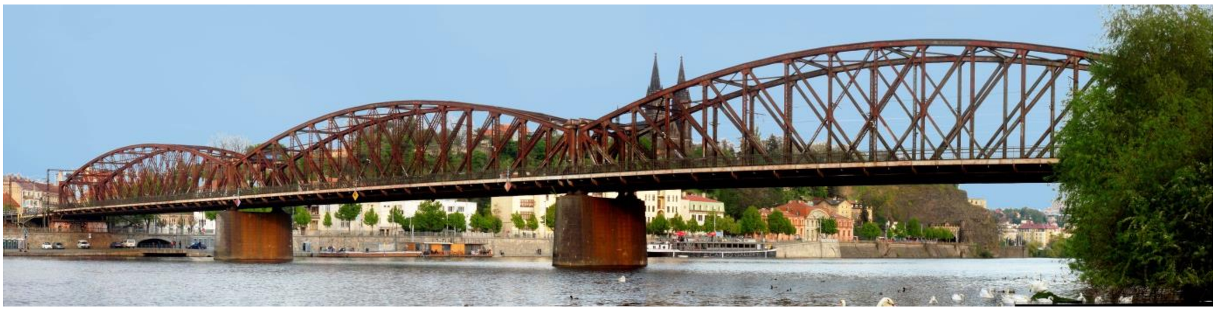

Figure 6. General view of the steel railway bridge in Prague.

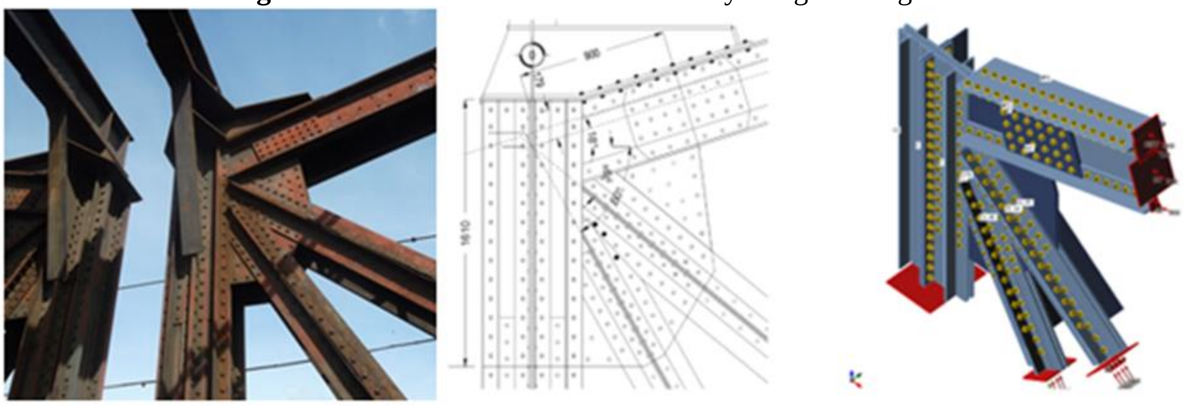

Figure 7. Connection C-02 on railway bridge in Prague, its drawing and its CBFEM model.

The Figure 8 shows the typical detail of the stringer to cross beam joint that is present on many steel bridges. Beams are riveted I profiles, with flanges made from riveted angles. Also connection was done by riveting of angles to the web of both elements. The model allows to analyse the rotational initial stiffness in both directions that can be directly inserted in the global numerical model. Especially this type of joint and also the connection between cross beam and main girder are essential for the load capacity assessment and the stiffness significantly influence the final result.

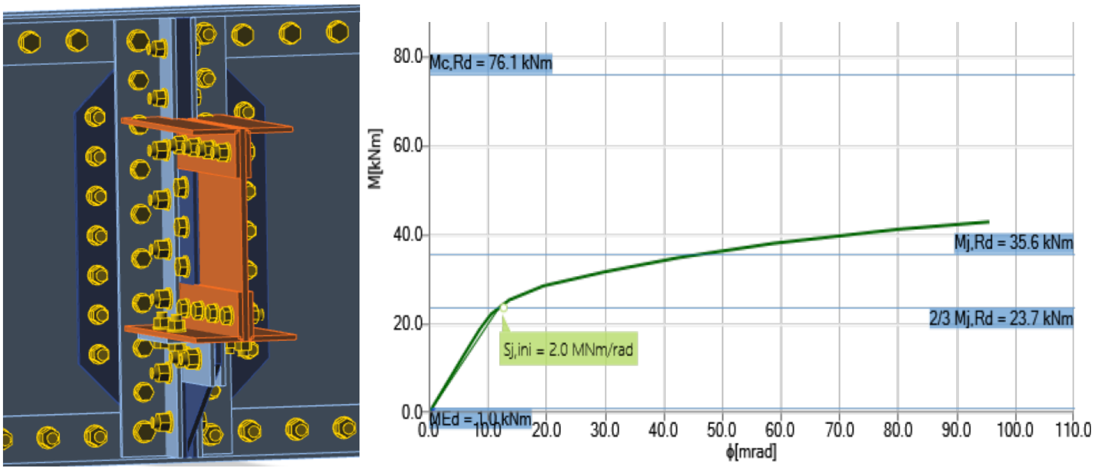

Figure 8. Stringer to cross beam connection on railway bridge in Prague and its moment rotational diagram by CBFEM model.

Seven bridges were analysed with all modelled details on each structure. This amount of data can be plotted in the summary diagram, as shown on the Figure 9. This graph can help to roughly predict the joint stiffness even without the time consuming analysis.

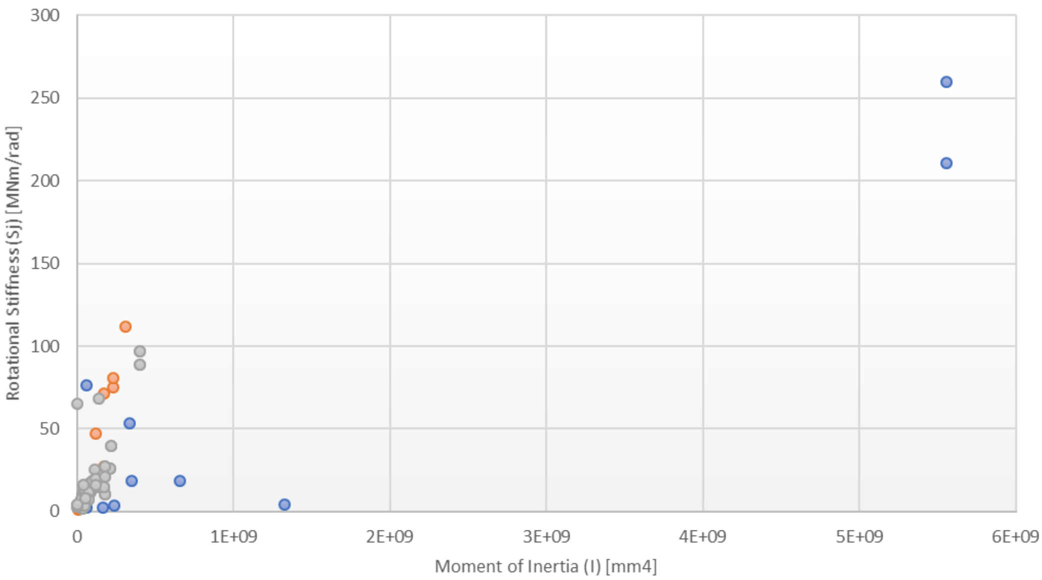

Figure 9. Summary of the results from seven analysed bridges, different symbols represents individual bridges.

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4. Conclusion
The global analyses of steel structures is today carried out by FEA and all the traditional procedures are not used any more. In new generation of structural Eurocodes after 2021 is expected to stress the principles of safety of applications of FEA by System response quantity process in EN1993-1-14:2021. The FEA analyses of the structural steel connections is replacing the curve fitting and component design methods. For its proper use is necessary to apply a good Validation and Verification procedures with well-defined hierarchy to allow a safe use.

The presented results show the good accuracy of CBFEM verified to CM and to advanced calculations/experiments in cases where the CBFEM gives higher stiffness, resistance, or deformation capacity, see [8]. The prediction of bolts as component by spring models allow accurate prediction of bolted connection resistance, stiffness and deformation capacity takin into account the initial elastic and post elastic stages.

That CBFEM helped to improve the global numerical models of old steel bridges and keep them in the service for the longer time. This is a beneficial result for the budget of the owners and lovers.

5. Announcement
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