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STRENGTH OF CONNECTIONS BETWEEN SHS COLUMNS AND THROUGH PLATES

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Abstract

The use of Square-Hollow-Section (SHS) members as columns of moment-resisting frames is a very interesting solution thanks to several benefits they can provide: (i) high values of the radius of gyration; (ii) absence of a weak axis; (iii) reduction of the paintings, fire and corrosion protection costs thanks to the low surface area, compared to the double-tee profiles; (iv) lower drag coefficients affecting wind forces; (v) higher aesthetical aspect.
However, especially in Europe and the USA, the use of SHS columns is limited by the complexity related to the realisation of beam-to-column connections. Nevertheless, the recent use in civil engineering of Laser Cutting Technology (LCT) has offered the opportunity to manufacture welded connections by properly cutting the tubular profile with the imprint of the cross-section shape of the double-tee member. Such a solution is an improved alternative to the joint with the I-beam welded to the external surface of the hollow profile since higher flexural strength and stiffness can be provided.
Considering the importance of such a topic, this connection is currently being studied at the University of Salerno within the framework of the component method approach. In this view, the research activity discussed in this paper studies the monotonic behaviour experienced by welded connections between SHS tubes and through-all plates. In fact, this component is representative of the actions applied on the tube by each of the beam flanges of a double-tee profile. In particular, this nodal component has been studied thanks to numerical simulations carried out in IDEAStatica, and theoretical approaches derived by applying the yield-line and yield-field methods, leading to analytical design formulations.

Keywords: component method, laser cutting technology (LCT), FEM, yield-line, yield-field

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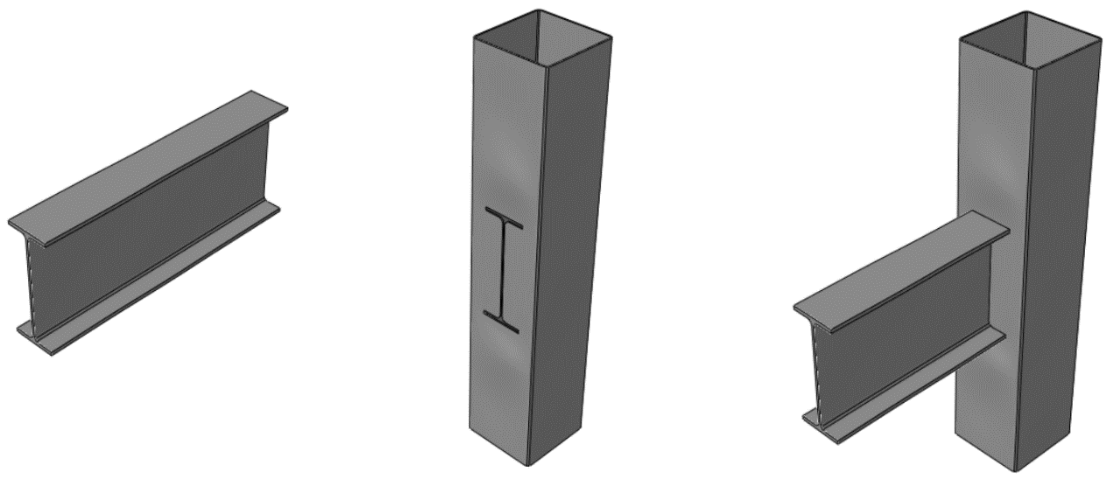
1 INTRODUCTION

The recent exploitation of 3D-Laser Cutting Technology (3D-LCT) in Civil Engineering has allowed the manufacturing of new welded beam-to-column connections characterised by tubular columns [1-2] and passing-through beams. An example of this solution is provided by joints between Circular-Hollow-Section (CHS) and through-all IPE profiles recently studied in the framework of the LASTEICON research project [3-5] and at the University of Salerno [6-9]. The manufacturing process consists in cutting the column according to the imprint of the beam so that it can cross the tubular profile; finally, the two members can be welded.

From a technological point of view, the improvements of this solution consist in the simplification and greater accuracy of the manufacturing process compared to the traditional nodal details [10-13]. In fact, it avoids using collar plates [11, 12], additional stiffeners [12] and composite columns [13]. Furthermore, due to the high precision of this technology, smaller tolerances are needed in the cutting procedure, reducing slag, the heat-affected zone (HAZ) and saving time. Instead, concerning the mechanical response, this approach allows for obtaining connections able to provide higher strength and stiffness compared to the traditional solutions with the beams externally welded to the columns. This evidence has been proven by the LASTEICON project investigation [3-5] and studies carried out at the University of Salerno [6-9]. In particular, the research is still ongoing and has been developed according to the spirit of the component method approach [10, 14]. This strategy allows the evaluation of the mechanical behaviour of beam-to-column connections through the response of their components defined employing bilinear phenomenological models. The component method approach has been widely applied in common practice since standardised rules are available for welded and bolted configurations joining double-tee members [10, 15-19]. Nevertheless, very few guidelines deal with applying this method to connections with tubular columns.

Referring to this knowledge gap, another line of study has recently begun at the University of Salerno, focused on assessing the flexural response of joints between Square-Hollow-Section (SHS) profiles and passing-through IPE beams (Figure 1).



a) Passing-through beam b) Column c) SHS to through-all IPE connection

Figure 1: Isolated members (a,b) and assembly of the connection (c).

The methodology to be adopted is inspired by the same one employed for connections with CHS columns; it consists in:

i) identifying the main sources of deformability of the joint;
ii) proposing analytical formulations for the strength and stiffness characterisation of the nodal components and combining them to obtain the flexural response of the whole joint;

iii) performing experimental tests on the components and beam-to-column sub-assemblies;
iv) modelling the tested specimens through one or more Finite Element software and validating them against the experimental results;
v) exploiting the validated FE models to perform parametric analyses on more comprehensive sets of sub-assemblies;
vi) assessing the accuracy of the proposed formulations against the results of the parametric analyses.

This work can be situated at the beginning of the previous list and aims to investigate the strength of the component representative of the actions transmitted by the flanges of the beam when it is subjected to bending. For this reason, the paper is focused on studying the behaviour of connections between SHS profiles and through-all axially loaded plates (Figure 2). In particular, theoretical formulations to predict the strength of the analysed component are defined according to the yield-line (YL) and yield-field (YF) methods (Figure 2). The accuracy of the derived equations is assessed against the results of a parametric analysis carried out on a set of 39 geometrical configurations of SHS to through-all axially loaded plate connections numerically modelled in finite element software.

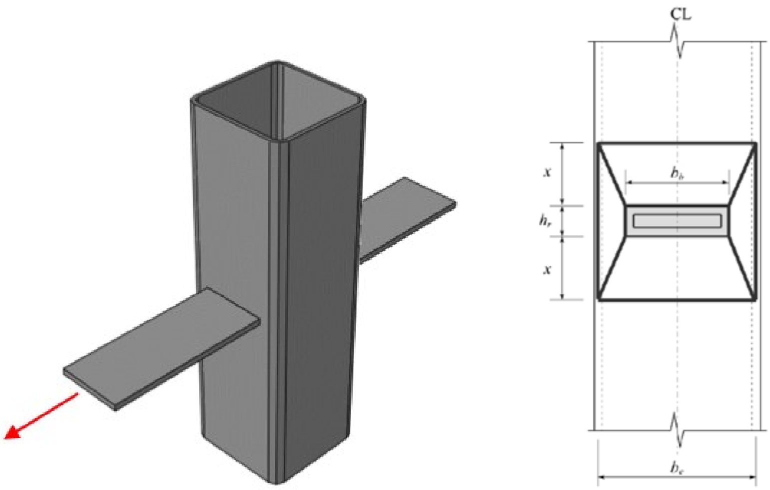


Figure 2: SHS with passing-through plate connection (left) and expected yield-line pattern (right).

2 ANALYTICAL FORMULATIONS

This section proposes formulations that estimate the plastic resistance of the analysed component, whose critical part is the tubular section close to the attachment with the plate. The proper approach to study this detail refers to the kinematic method of Limit Analysis [20-22] and, in particular, to some of its applications, known as yield-line and yield-field methods [23-25].

The Limit Analysis relies on two approaches:

i) the first one is based on the energy method and consists in equating the work induced by external loads for an assigned configuration of virtual displacements and the internal work induced by the plastic hinges or yield-lines (kinematic approach);
ii) the second one requires the fulfilment of the equilibrium (static approach).

The two approaches define an interval in which the value of the ultimate load is included; in particular, the static method allows the assessment of the lower extreme, while the kinematic method defines the upper one. In the spirit of the Limit Analysis, an iterative procedure is needed to accomplish the solution since the collapse mechanism and the load distribution should be defined according to the kinematic and static methods, respectively, until they provide the same ultimate load. However, the static procedure is difficult to apply due to equilibrium and resistance conditions to be satisfied; instead, the kinematic method represents a straightforward technique because it provides the ultimate capacity of the connection as the minimum load assessed among all the possible collapse mechanisms.

The yield-line and yield-field methods represent applications of the kinematic approach, which are able to investigate the diffusion of yielding not in punctual sections, as it happens in the case of the framed buildings, but along linear patterns, defined as yield-lines. In fact, referring to the analysed component, the axially loaded plate induces a stress distribution on the faces of the tube, which, increasing, creates a pattern of plastic deformations (Figure 3), causing the collapse of the connection. Consequently, a simple way to mechanically model the analysed joint consists in studying the behaviour of a rectangular plate which is representative of the face of the tube subjected to forces applied by the plate (Figure 3).

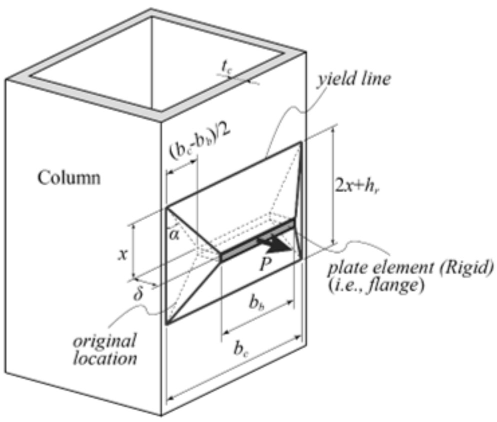
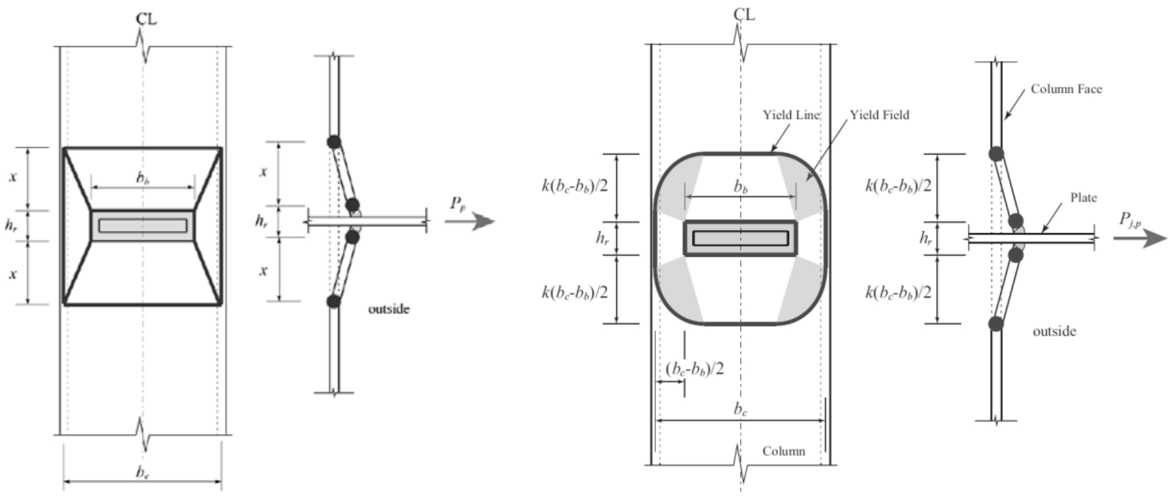


Figure 3: Expected yield-lines distribution in the tube.

The yield-line and yield-field methods provide the upper bounds of ultimate loads that the faces of the tube can withstand, provided that the collapse mechanism has been correctly individuated. The main difference between these strategies is that in the yield-field method some yield-lines are substituted by a region which experiences plastic deformation (Figure 4).



a) Yield-lines only b) Yield-lines and yield-fields

Figure 4: Yield-lines and yield-fields at the column face.

The formulation to assess the strength of the analysed component with the yield-line (YL) method ($F_{j,pl,YL}$) is assessed by applying the work principle considering the collapse mechanism shown in Figure 4a. It is reported in Eq. (1).

$$F_{j,pl,YL} = 8M_0\left(\frac{b_0}{x} + \frac{4x}{b_0 - b_1} + \frac{2t_1}{b_0 - b_1}\right) \tag{1}$$

In Eq. (1) $M_0 = \frac{1 \cdot t_0^2}{4} f_{yk}$ is the bending moment for the unitary width of the tube, t_0 is the thickness of the tube, f_{yk} is the yield stress, $b_0 = B_0 - t_0$, B_0 is the external width of the SHS, b_1 and t_1 are the width and the thickness of the plate, respectively, x represents the distance of the farthest yield-line from the rectangular hole. According to the kinematic theorem, the unknown parameter x is assessed by minimising the function $F_{j,pl,YL} = F_{j,pl,YL}(x)$, and it is shown in Eq. (2).

$$x = \frac{\sqrt{b_0(b_0 - b_1)}}{2} \tag{2}$$

Consequently, it results:

$$F_{j,pl,YL} = 8M_0\left(4\sqrt{\frac{b_0}{b_0 - b_1}} + \frac{2t_1}{b_0 - b_1}\right) \tag{3}$$

The same approach is applied to the yield-field (YF) method; however, since some regions are subjected to plastic deformations in this case (Figure 4b), a more complex formulation has been obtained, Eq. (4).

$$F_{j,pl,YF} = 8M_0\left[\pi + \frac{4}{\pi}(\ln k)^2 + \frac{2}{b_0 - b_1}\left(t_1 + \frac{b_1}{k}\right)\right] \tag{4}$$

In Eq. (4), k is a parameter to be assessed according to Eq. (5), an equation that cannot be solved in a closed form.

$$k = \frac{8}{\pi}\ln k - \frac{2b_1}{k(b_0 - b_1)} \tag{5}$$

3 PARAMETRIC ANALYSIS AND NUMERICAL SIMULATION

The assessment of the accuracy of the proposed formulations needs a comprehensive collection of data to which a proper comparison can be carried out. To this aim, a parametric analysis has been performed by selecting a set of 39 geometric configurations of the analysed joint. The cases have been chosen by varying the tube width between 160 and 300 mm, the tube thickness between 6 and 12.5 mm, the plate width between 100 and 230 mm, and the plate thickness between 20 and 45 mm (Table 1). It has been assumed that all the structural members are made of S355 steel grade.

The selected cases have been numerically modelled employing IDEAStatica software (Figure 5), a Component-Based Finite Element (CBFEM) tool [26] used to design and check steel connections integrating the component method in the finite element modelling. The geometries of the members have been selected by catalogues; instead, the detail of the plate passing through the tube has been realised through specific cutting tools implemented in the software. It is worth highlighting that, differently from more advanced software able to model the solid tridimensional geometry of the connections, IDEAStatica assumes that the SHS and the plate are modelled through shell elements. The welds have not been explicitly modelled. Each of the selected 39 connections has been loaded with monotonic tensile axial forces applied to the plate. The ultimate strength has been assessed at the attainment of 5% of principal plastic deformation according to Eurocode 3 part 1.5 requirement [27]. The results of the analyses are collected in Table 1. For the sake of clarity, the equivalent stress distribution and the plastic deformation experienced by case 39 are shown in Figure 6 and Figure 7.

Case	Tube width b_0 (mm)	Tube thickness t_0 (mm)	Plate width b_1 (mm)	Plate thickness t_1 (mm)	IDEAStatica strength (kN)
1	160	6	100	20	178.6
2	160	6	100	25	180.1
3	160	6	100	30	185.8
4	160	6	100	35	187.5
5	160	6	100	40	191.7
6	180	6	120	20	184.5
7	180	6	120	25	185.8
8	180	6	120	30	192.7
9	180	6	120	35	193.7
10	180	6	120	40	199.2
11	220	10	150	25	441.7
12	220	10	150	30	446.6
13	220	10	150	35	450.3
14	220	10	150	40	476.6
15	220	10	150	45	468.8
16	300	12	230	20	770.8
17	300	12	230	25	799.7
18	300	12	230	30	906.3
19	160	8	100	25	312.5
20	160	8	105	25	311.0
21	160	8	110	25	315.5
22	160	8	115	25	418.2
23	160	8	120	25	413.2
24	180	10	100	25	458.3
25	180	10	105	25	465.8
26	180	10	110	25	471.7
27	180	10	115	25	471.7
28	180	10	120	25	446.2
29	180	10	125	25	446.2
30	220	12	100	25	528.3
31	220	12	110	25	482.1
32	220	12	120	25	645.8
33	220	12	130	25	647.6
34	220	12	140	25	564.2
35	300	12.5	120	25	505.2
36	300	12.5	125	25	508.7
37	300	12.5	130	25	510.4
38	300	12.5	135	25	513.9
39	300	12.5	140	25	517.4

Table 1: Selected cases for the parametric analysis.

Figure 5: Connection modelled in IdeaStatica (case 39).

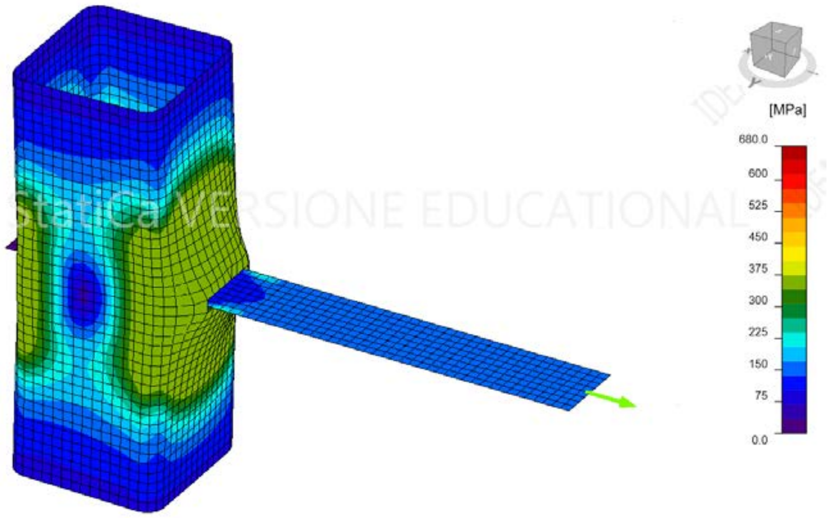


Figure 6: Equivalent stress distribution (case 39).

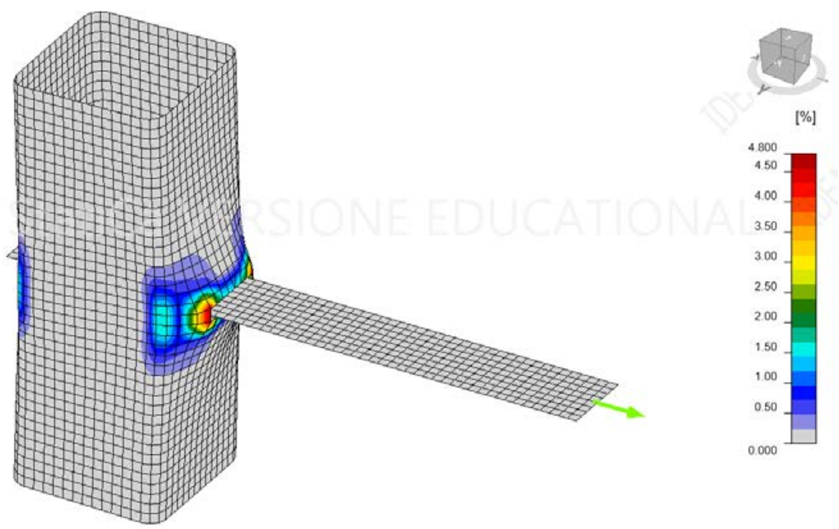


Figure 7: Plastic deformation (case 39).

4 VALIDATION OF THE PROPOSED FORMULATIONS

This paragraph evaluates the accuracy of the proposed formulations. Table 2 shows the results provided by IDEAStatica and the ultimate loads withstood by the analysed 39 cases when the two proposed formulations are applied.

Case	Strength (kN)			YL/IS	YF/IS
	IDEAStatica (IS)	Yield-line method (YL)	Yield-field method (YF)		
1	178.6	191.6	162.2	1.07	0.91
2	180.1	196.3	166.9	1.09	0.93
3	185.8	201.1	171.6	1.08	0.92
4	187.5	205.8	176.4	1.10	0.94
5	191.7	210.5	181.1	1.10	0.94
6	184.5	202.5	171.1	1.10	0.93
7	185.8	207.2	175.8	1.12	0.95
8	192.7	211.9	180.6	1.10	0.94
9	193.7	216.7	185.3	1.12	0.96
10	199.2	221.4	190.0	1.11	0.95
11	441.7	590.5	499.3	1.34	1.13
12	446.6	602.3	511.1	1.35	1.14
13	450.3	614.2	522.9	1.36	1.16
14	476.6	626.0	534.8	1.31	1.12
15	468.8	637.8	546.6	1.36	1.17
16	770.8	981.8	818.9	1.27	1.06
17	799.7	999.4	836.5	1.25	1.05
18	906.3	1017.2	854.1	1.12	0.94
19	312.5	354.5	301.5	1.13	0.96
20	311.0	375.2	319.3	1.21	1.03
21	315.5	399.9	340.4	1.27	1.08
22	418.2	429.8	365.6	1.03	0.87
23	413.2	467.1	396.8	1.13	0.96
24	458.3	493.3	417.6	1.08	0.91
25	465.8	513.9	435.6	1.10	0.94
26	471.7	537.2	455.8	1.14	0.97
27	471.7	563.9	478.7	1.20	1.01
28	446.2	594.7	504.9	1.33	1.13
29	446.2	630.9	535.5	1.41	1.20
30	528.3	614.9	515.6	1.16	0.98
31	482.1	648.0	545.0	1.34	1.13
32	645.8	686.8	579.2	1.06	0.90
33	647.6	733.4	619.6	1.13	0.96
34	564.2	790.4	668.4	1.40	1.18
35	505.2	614.5	510.7	1.22	1.01
36	508.7	624.4	519.7	1.23	1.02
37	510.4	634.8	529.0	1.24	1.04
38	513.9	645.7	538.7	1.26	1.05
39	517.4	657.1	548.9	1.27	1.06
			Mean	**1.20**	**1.00**
			Standard deviation	**0.11**	**0.09**
			Coefficient of variation	**0.09**	**0.09**

Table 2: Validation of the proposed formulations.

Furthermore, Table 2 collects the ratios between the values of strength provided by the analytical solutions and the numerical simulations. These data highlight that, on average, the yield-field method is able to predict the ultimate strength with better accuracy than the yield-line since the mean value of the ratios is equal to 1.00 against 1.20. Instead, in both cases, the coefficients of variations are equal to 9%. The reason which justifies the better prediction of the proposal based on the yield-field approach is probably ascribed not only to the greater refinement of the method but also to the limits of the CBFEM modelling strategy. In fact, IDEAStatica models the tube and the plate with shell elements, approximating some effects associated with the thickness of the elements.

5 CONCLUSIONS

The present paper has dealt with studying one of the components of SHS to through-all I-beam connections, which is the plate transversally welded to the square tubular profile in tension/compression. In fact, this component is representative of the behaviour of the flanges of the beam welded to the SHS member.

The research concerned the definition of formulations to predict the strength of the analysed component. In particular, the proposed equations have been derived from the application of the yield-line (YL) and yield-field (YF) theories and have been validated against the results of a parametric analysis carried out on a set of 39 SHS to though-all plate connections whose behaviour has been numerically simulated thanks to IDEAStatica software.

The comparison between the analytical and numerical outcomes has shown that the yield-field method can predict the connection's resistance with higher accuracy than the yield-line approach. In fact, the mean of the ratios between the analytical and numerical outcomes is equal to 1.00, referring to YF, and 1.20 referring to YL. This difference is probably due to the limits of the modelling approach provided by IDEAStatica, which models the tube and the plate according to shell members. In both cases, the coefficients of variation of the ratios among the proposals and the FEM results are equal to 9%.

Further studies will validate these results by modelling the analysed cases with more refined FE software that can create a solid modelling of the members to clarify the previous difference.

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